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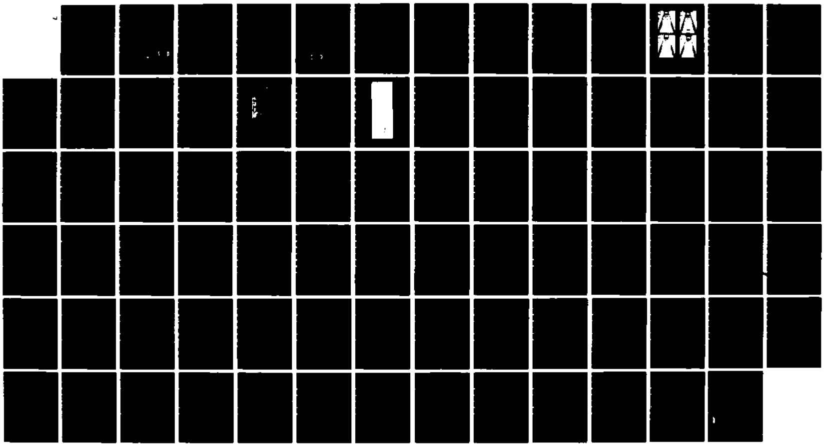

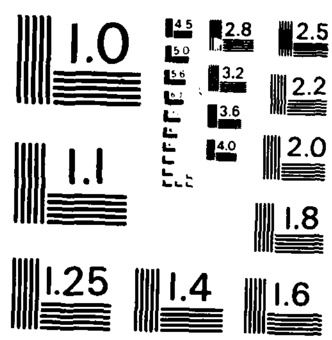

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NRL Memorandum Report 5337

The Breaking of Ocean Surface Waves

O. M. GRIFFIN

Fluid Dynamics Branch
Marine Technology Division

AD-A142 356

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There are essentially four types of breaking waves, as described by Galvin (1968) and many others. The first two types are the plunging breaker, in which the wave crest curls forward and plunges into the slope of the wave at some distance away from the crest; and the spilling breaker, in which the broken region tends to develop more gently from an instability at the crest and often forms a quasi-steady whitecap on the forward face of the wave. The third type, surging, sometimes develops as waves are incident upon a sloping beach. A fourth type of breaking, collapsing, is considered by many to be a special limiting case of the plunging breaker. Several advances toward an understanding of wave breaking have been made in recent years. These include the experimental characterization of the instability mechanisms which lead to wave breaking in deep water, proposed mathematical models for these instability mechanisms, and numerical simulations of wave overturning and incipient breaking. These topics are discussed here.

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19. ABSTRACT (Continued)

Little is known quantitatively about the processes of air entrainment in breaking waves. However, a more complete knowledge of the air entrainment processes will be required for the further development of plausible models for radar scattering from breaking waves on the ocean surface.

A forecast model for the breaking of deep water waves has been proposed and a breaking criterion for use with the model has been formulated. Recent laboratory experiments to study the onset of wave breaking in deep water provide one means for quantifying this criterion in terms of a breaking coefficient. An alternate means for determining this coefficient has been proposed on the basis of stream function wave theory. These topics also are discussed here.

CONTENTS

THE BREAKING OF OCEAN SURFACE WAVES

1. INTRODUCTION

There are many causes for the breaking of ocean waves. These include the relative motion between the water and, say, a ship in the seaway or a cylindrical obstacle in a wavefield; wind blowing over the water; superposition of and nonlinear interactions between wave components; concentration of wave energy by refraction; and the shoaling of waves. These various causes result in two predominant types of breaking waves: the plunging breaker, in which the wave crest curls forward and plunges into the slope of the wave at some distance away from the crest; and spilling breakers, in which the broken region tends to develop more gently from an instability at the crest and often forms a quasi-steady whitecap on the forward face of the wave.

A third type, surging, sometimes develops as waves are incident upon a sloping beach. In this case, if the slope is very steep or the wave steepness is very small, the waves do not actually break but surge up and down to form a standing wave system with little or no air entrainment. A fourth case, collapsing, is considered to be a special limiting case of the plunging breaker. Collapsing occurs when the crest remains unbroken, but the lower part of the front face of the wave steepens and falls and then forms an irregular region of turbulent water. Galvin (1968) has provided a historical survey of the evolution of these wave breaking characterizations.

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Wave breaking is an important consideration in surface ship hydrodynamics for a number of reasons. The wave resistance or drag on the ship is influenced by the breaking of the ship's bow wave. Also the energy balance and the ensuing white water production in the downstream Kelvin wave pattern must account for any energy losses due to breaking. Inclusion of breaking wave effects and valid onset criteria are important factors in the development of general analytical or numerical models for the downstream turbulent wake and wave fields produced by the motion of a surface ship in a seaway.

Several advances toward an understanding of wave breaking have been made in recent years. These include the experimental characterization of the instability mechanisms which lead to wave breaking in deep water, mathematical models for the instability mechanisms, and numerical simulations of wave overturning and incipient breaking. Empirical and semi-empirical models have been proposed to describe the breaking of steady and 'quasi-steady' waves. The latter category includes steady waves generated by the relative motion between the water and submerged bodies, the later stages of spilling breakers, tidal bores, and hydraulic jumps.

2. CHARACTERISTICS OF BREAKING WAVES

The general features of breaking waves in deep and shallow water are known from observation. However, the actual physical processes that contribute to the breaking are not well understood for the most part, although progress has been made in the past few years. General discussions of the physical processes involved in wave breaking are given by Galvin (1968) and by Cokelet (1977). More recently Kjeldsen and Myrhaug (1978) and Melville (1982) have described those factors which are most relevant to understanding the breaking of waves in deep water. Peregrine (1979,1983) has reviewed what is known (and

not known) about the overall dynamics of wave breaking and, particularly, about the breaking processes in shallow water and on beaches.

Kjeldsen and Myrhaug (1979), and Kjeldsen, Vinje and Brevig (1980) have conducted experimental and numerical studies of wave breaking in deep water. Both plunging and spilling breakers were identified from the results of wave channel experiments. In addition a so-called deep water bore was found to exist under certain conditions. The breaking of the waves was caused by the creation of a convergence zone in a wave channel, and by the interaction of the basic wave with both superharmonic and subharmonic disturbances. Peregrine (1979) has summarized the findings of a recent colloquium on wave breaking on beaches and in shallow water. The conclusions summarized then by Peregrine have not changed substantially at the present time, i.e. that the theoretical study of breaking waves is in its infancy and that experimental studies are beginning to give a good picture of the kinematics of wave breaking.

The various types of breakers are sketched in Figure 1, which is adapted from the original work of Galvin (1968). A breaking wave has been defined in one way as a wave in which fluid particles on the free surface in the region of the crest are moving at a speed greater than the phase speed of the overall wave profile (Banner and Phillips, 1974). This criterion may not be true in general. There generally are three regimes of breaking waves. They are:

- Deep-water waves;
- Waves on beaches and in shallow water;
- Steady and 'quasi-steady' waves (some of which may fall into either or both of the above categories).

Kjeldsen and Myrhaug (1978) conducted a detailed review of work on wave breaking up to that time. All aspects of wave breaking,

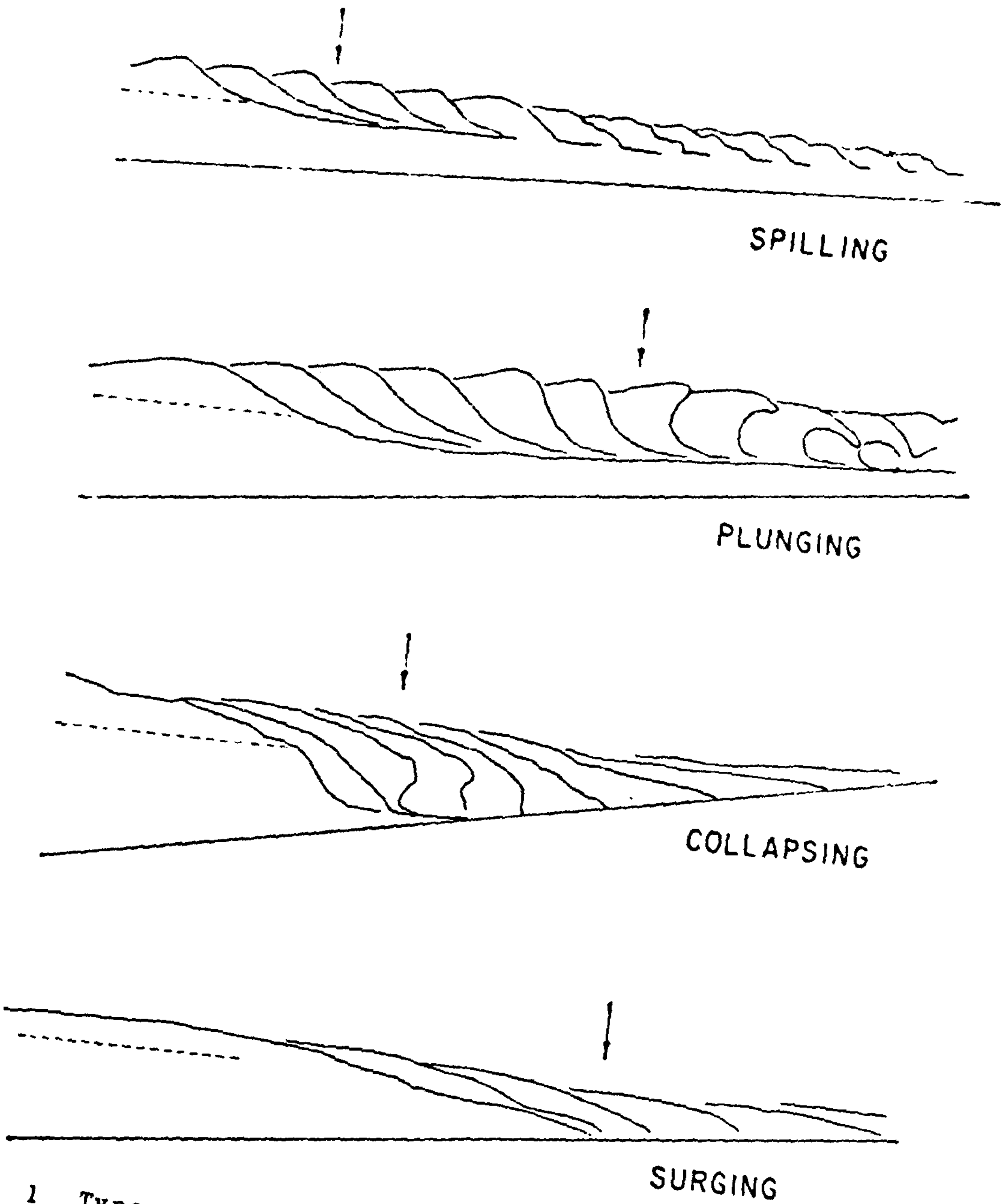

Figure 1 Types of breaking waves; adapted from Galvin (1968).

primarily in deep water, were considered. A preliminary model was proposed for defining the occurrence of breaking in deep water. This model was derived from the the previous work of Nath and Ramsey (1974) on a similar problem. Kjeldsen and Myrhaug adopted the first appearance of air entrainment or "white water" at the wave crest as their criterion for the initiation of wave breaking.

A detailed study of the evolution to breaking of deep-water waves was undertaken recently by Melville (1982). Two distinct regimes were found. For $ak \leq 0.29$ the evolution was two-dimensional with the Benjamin-Feir instability (Benjamin, 1967; Benjamin and Feir, 1967) leading directly to breaking. For $ak \geq 0.31$ a full three-dimensional instability dominated the Benjamin-Feir instability and rapidly led to wave breaking. Here a is the wave amplitude and k is the wave number. In 1967 Benjamin and Feir had demonstrated that weakly nonlinear surface waves are unstable to side-band disturbances. Typical spilling breakers as observed by Melville (1982) at two wave steepnesses are shown in Figure 2.

Several years ago Longuet-Higgins (1978a,1978b) examined the stability of strongly nonlinear waves to small perturbations. The Benjamin-Feir instability was confirmed as an asymptotic result for small wave steepness and a strong instability was found at $ak = 0.41$. Longuet-Higgins (1978b) proposed that this instability corresponded to the incipient stages of a plunging breaker. Longuet-Higgins and Cokelet (1978) later confirmed this proposition in a numerical simulation of incipient wave breaking. The numerical experiments demonstrated that waves with their initial steepness as small as $ak = 0.25$ evolved to breaking at local steepness values near 0.39. This is somewhat less than the limiting wave steepness of $ak = 0.443$.

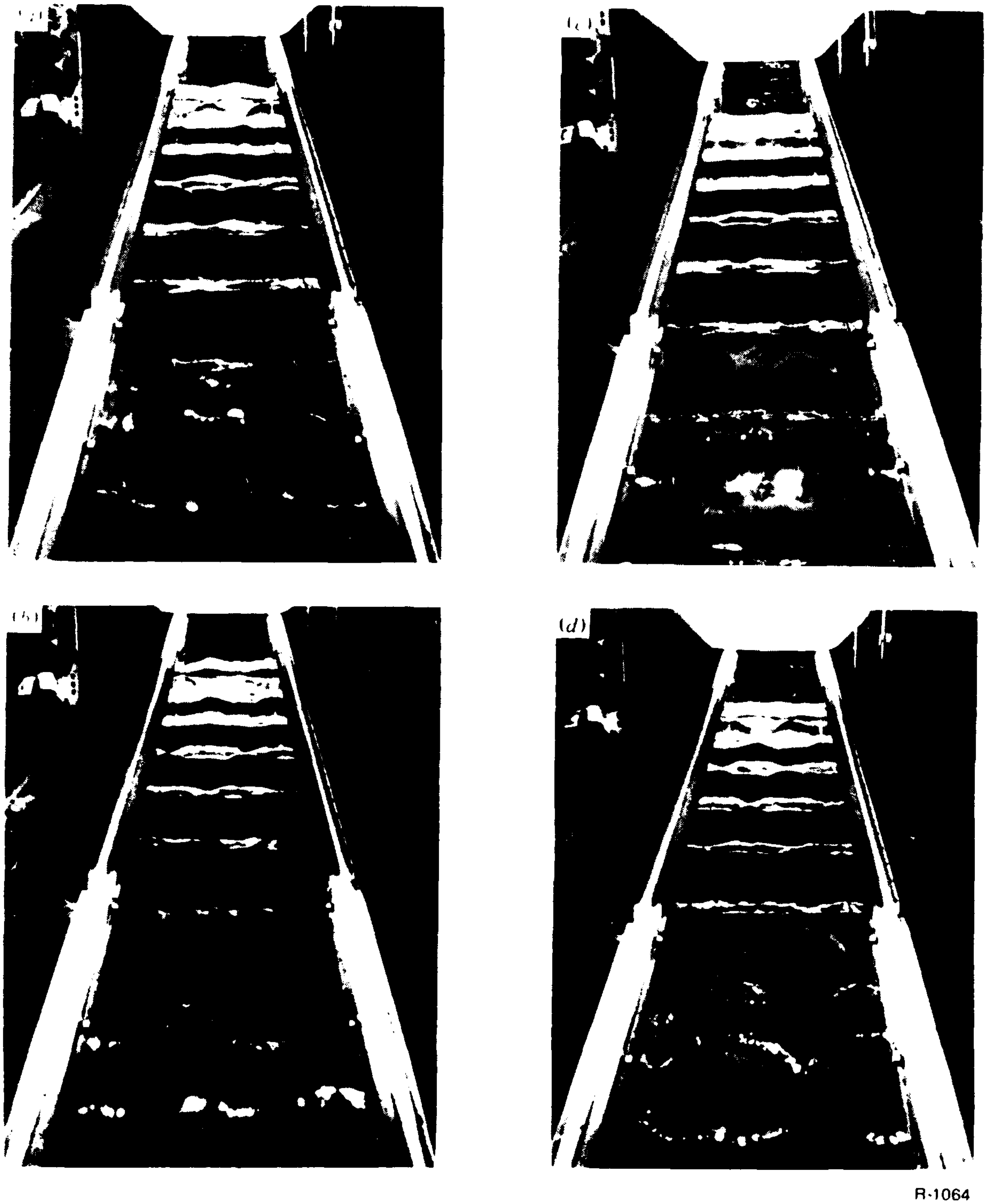

Figure 2 Spilling breakers in a laboratory wave channel; from Melville (1982). Left hand column, ak = 0.315; right hand, ak = 0.321.

Su et al (1982) also have conducted an experimental study of steep gravity wave instability in deep water. The initial wave steepness was in the range $0.25 \leq ak \leq 0.34$. It was found that an initial two-dimensional wave train of large steepness evolved into a three-dimensional train of spilling breakers and then into a series of modulated wave groups of lower steepnesses and frequencies. Su et al (1982) achieved qualitative agreement with several aspects of the previous work of Longuet-Higgins, i.e. the appearance of subharmonic instabilities and the fast evolution to breaking upon the appearance of rapidly-growing instabilities at critical values of the wave steepness. However, the laboratory waves were three-dimensional spilling breakers whereas the numerical simulation was limited to two-dimensional plunging breakers. Cokelet (1977) has noted that both plunging and spilling breakers can occur in deep water, though spilling is the more common of the two. It was clear from the experiments that the subharmonic instabilities played an important role in the breaking of steep gravity waves in deep water.

The wave channel experiments of Melville and of Su et al generally produced waves that spilled over the wave crest without significant white-capping. Waves in the ocean typically entrain air during the breaking process and the formation of a white cap or "white water" region on the forward face of the wave is common. The air entrainment process sometimes can play an important or even dominant role in the wave breaking.

Longuet-Higgins and Turner (1974) proposed an 'entraining plume' model of a spilling breaker in which the white water region was modelled as a turbulent gravity current on the forward face of the wave. Peregrine and Svendsen (1978) later proposed that the final stages of evolution of the spilling breaker are quasi-steady and that the white water region can be modelled as a form of turbulent mixing layer. The mixing layer

arises because the smooth wave flow from upstream meets the slowly moving fluid in the toe of the surface roller. It was assumed that the roller plays a relatively unimportant role in the wave dynamics, except to initiate the downstream turbulent flow.

A model for predicting the surface profiles and velocity fields of turbulent bores and hydraulic jumps in shallow water has been introduced by Madsen and Svendsen (1983). A depth-integrated method of solution is combined with a $k-\varepsilon$ turbulent closure model to simulate the flow field near the toe of the breaker. The theory is based upon the observations of Peregrine and Svendsen (1978). This approach may be applicable to modeling the turbulent region of a deep water breaker since Madsen and Svendsen ignored the bottom boundary layers in a bore and jump and concentrated their attention on the turbulent flow region in the front and near the surface of the discontinuity.

Stive (1980) measured the velocity and pressure fields of spilling breakers and found the internal flow field to agree qualitatively with the model proposed by Peregrine and Svendsen. However, the dynamics of the white water region are not well defined and further work to characterize them clearly is essential to a complete understanding of breaking wave dynamics.

Waves on sloping beaches and in shallow water most commonly break by plunging, although spilling, collapsing and surging also do occur. Collapsing appears to be a limiting case of the plunging process as the deep water wave height to wave length ratio tends toward very small values ($2ak \approx 0.01$). A detailed experimental characterization of the plunging breaker on a sloping beach has been made by Hedges and Kirkgoz (1981). The plunging process was thought to start at the location where the wave becomes asymmetrical about a vertical line through its

crest. This point is seaward of the actual breaking point, which is defined by Hedges and Kirkgoz as the location where some part of the front face of the wave first becomes vertical. After the wave passes the breaking point a sheet of water is projected forward from the wave crest. This sheet of water curls over the front face of the wave and encloses an air pocket as it falls. Then this turbulent mixture of entrained air and water runs up the slope.

Hedges and Kirkgoz used a laser anemometer to measure the velocity field in the waves prior to breaking. All of the measurements were made in the transformation zone, i.e. the horizontal region between the transformation point and the breaking point of the waves. The distribution of horizontal velocity with depth was dependent primarily on the slope of the beach upon which the breaking was taking place. It also was found by them that the velocities of the fluid particles near the wave crest were less than the phase speed of the wave as the plunging was initiated. The fluid particle velocities only equaled the phase speed at the larger values of deep water wave steepness and on mildly sloping beaches. These conditions were taken to be more characteristic of spilling breakers. Plunging of the breaking wave appeared to be due to differences in the fluid particle velocities in various parts of the breaker profile.

An analytical model for the initial stages of overturning prior to the plunging of the wave has been proposed by Longuet-Higgins (1982). Two examples of plunging breakers given by Longuet-Higgins (from Miller, 1976) are shown in Figures 3 and 4. The first of the two figures shows the initial stage of the overturning and the second shows the tip of the breaker striking the forward face of the wave.

At-sea measurements of both spilling and plunging breakers have been made by Keller, Plant and Valenzuela (1981) using a coherent microwave radar. The spilling breakers were measured in the relatively deep water (30 m) adjace : to a tower in the German sector of the North Sea. Plunging breakers were found to be more common at a shallow water (3 m) site on the North Carolina coast. One example from the former study is shown in Figure 5. A time sequence (time increasing from the top to the bottom of the figure) of the amplitude and doppler frequency of the radar return clearly shows the character of the underlying surface wave pattern. A Doppler frequency shift of 100 Hz corresponded to a line of sight velocity measured at the water surface by the radar of 1.6 m/s (3.1 kt). A breaking wave is shown by the region of wide-band radar return. Since the tower was in fairly deep water of constant depth it was assumed that the wave action was predominantly due to spilling breakers. Coherent microwave radar which yields both the amplitude and phase of the backscattered radar signal from the ocean surface appears to be a promising means for the measurement and characterization of wave breaking.

A first step toward deriving a model for radar scattering by spilling breakers has been taken by Wetzel (1981). In his development he utilized certain aspects of the entraining plume model put forward by Longuet-Higgins and Turner. It was necessary, however, to introduce several assumptions concerning the plume shape and a number of heuristic propositions in order to account for some of the observed properties of microwave scattering from breaking waves. Thus the plume model as yet is only a hypothesis whose plausibility must be established by further experiments to elucidate both the radar scattering characteristics and the hydrodynamics of wave breaking.

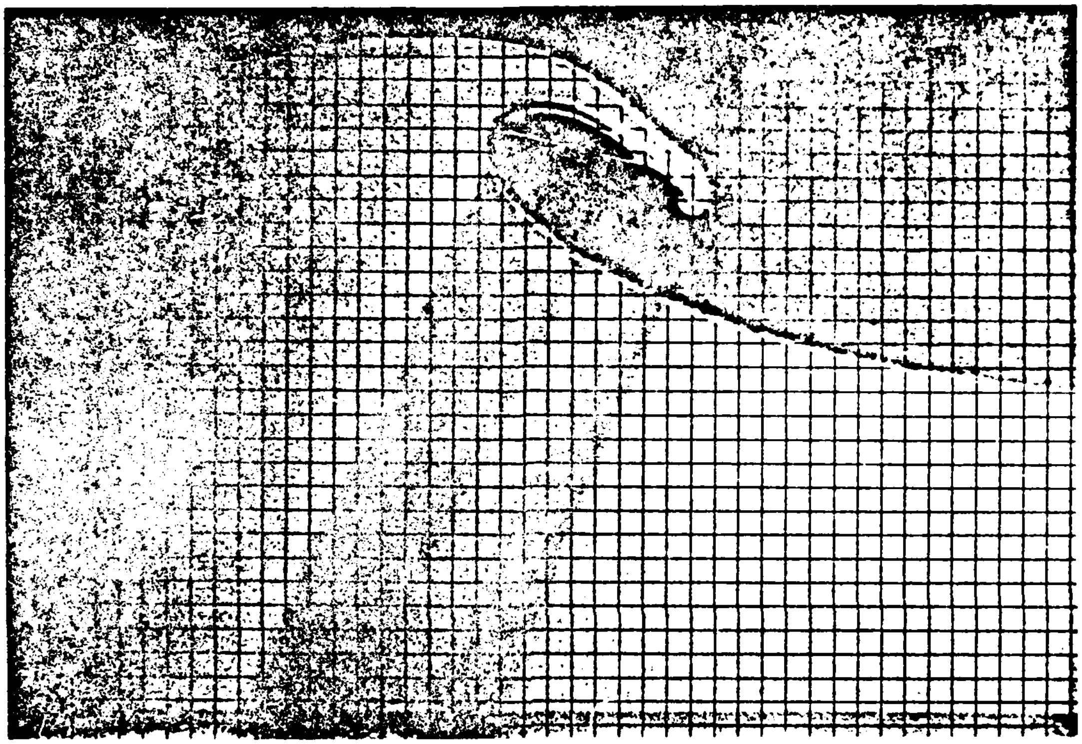

Figure 3 A profile of a plunging breaker; from Miller (1976). © SEPM, Special Publication No. 24, Miller, R.L., used by permission.

Figure 4 Tip of a plunging breaker striking the forward face of the wave; from Miller (1976).
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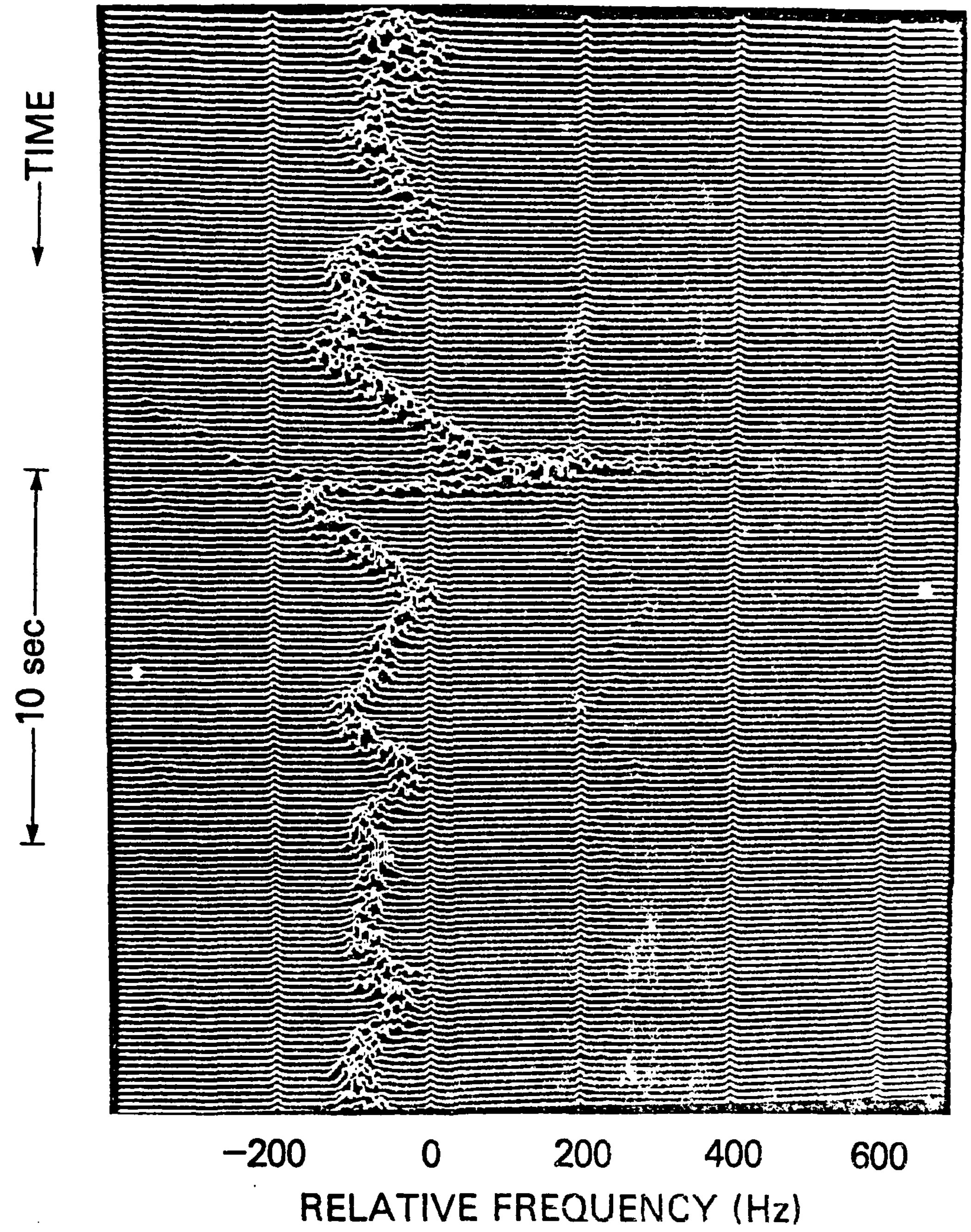


Figure 5 Doppler spectra of microwave backscattered power from the Nordsee Tower, German Bight (0.20 sec averages). In this case of strong deep water wave breaking the Doppler Spectral frequencies exceed 300 Hz; from Keller, Plant and Valenzuela (1981).

Banner and Phillips (1974) sought criteria for the incipient breaking of small scale waves. Of primary interest in their study was the effect of the surface drift due to wind on the spilling of the small scale waves. A quantitative criterion was developed for the limiting amplitude a_{MAX} of a steady wave in the presence of wind-generated drift currents. The proposed model was compared qualitatively with flow visualization photographs of a steady breaking wave in a laboratory channel. The wind flow over the surface produced a spilling breaker with a turbulent wake trailing downwind just below the water surface.

Steady or 'quasi-steady' breaking waves are common in a number of interesting hydrodynamic contexts. Peregrine and Svendsen (1978) define a 'quasi-steady' wave as one which changes little during the time a fluid particle takes to move through it. The transverse and diverging Kelvin wave patterns in the wake of a ship moving at constant speed are but two examples of steady waves. Others are bores, hydraulic jumps, and the surface wave patterns produced by submerged objects which are in steady motion relative to the fluid. Duncan (1981) studied experimentally the surface wave pattern produced by towing a hydrofoil steadily just beneath the surface at an angle of attack. Battjes and Sakai (1981) conducted a similar experiment by placing a hydrofoil section at an angle of attack below the water surface in a steady current flow. A breaking surface wave was produced just downstream of the trailing edge of the hydrofoil; the wave was similar in character to a spilling breaker.

A photograph of a typical breaker produced in Duncan's experiments is shown in Figure 6. The wave appears to have many of the characteristics of a spilling breaker. The breaking wave again was just downstream from the trailing edge of the hydrofoil, followed by a train of non-breaking waves and a turbulent wake just below the water surface. The wake thickness

Figure 6 A photograpn or tne turbulent wake of a breaking wave. A subsurface hydrofoil moving from right to left is shown in the lower left-hand corner of the photograph; from Duncan (1981).

at a given location was found to vary as $(\text{time})^{1/2}$ or, equivalently, $(\text{distance})^{1/2}$ downstream from the breaking wave. Duncan found a number of similarities in the geometry of the waves. The wave length, the wave height, and the vertical extent of the breaking region all were proportional to the square of the phase speed (c^2). The ratio of the breaking region thickness and length also was constant for all the conditions tested.

More recently Duncan (1983) has derived criteria for the incipient breaking of the steady waves produced by the motion of the submerged hydrofoil at an angle of attack. It was possible to induce steady breaking when the wave slope reached 17° and the wave steepness was $ak = 0.31$. Wake survey measurements downstream from the hydrofoil showed that the hydrodynamic drag on the hydrofoil due to the wave breaking was as much as three times the drag that theoretically would be caused by non-breaking waves.

Battjes and Sakai (1981) produced a steady breaker with a trailing subsurface wake at the free surface downstream from a hydrofoil. The experiment was run on two scales (one half of the other in terms of Froude number, and in hydrofoil depth and dimensions) with the same results, so that any Froude scaling effects were thought to be minimal. Measurements were made of the fluid velocity components in line with and normal to the incident flow direction at and downstream of the toe of the breaking wave. From these measurements estimates of the wake velocity defect, the Reynolds stress, and the shear layer thickness were obtained. A plane, self-similar turbulent wake was observed downstream from the breaker, with the wake variables just mentioned varying with the $(\text{distance})^{1/2}$ downstream from a virtual origin (or its reciprocal). The results obtained by Battjes and Sakai and by Duncan are complementary and qualitatively the same.

Experiments were conducted by Nakagawa (1983) to measure the three components of velocity in a plunging breaker. The tests were conducted in a laboratory wave channel where the breaking was initiated at an abrupt change in the depth of the channel. Spectral analyses of the measured velocities showed that the dominant frequencies survived in the longitudinal and vertical components after strong shoaling and breaking processes. Part of the wave energy was transferred to the transverse velocity component, in the direction of the wave crest, also at the dominant wave frequencies.

3. MATHEMATICAL AND NUMERICAL MODELLING OF WAVE BREAKING

No general analytical models presently are available to describe the time-dependent physical processes which take place during wave breaking. Those models which do exist refer to small amplitude waves that are characterized by low wave slopes and fluid accelerations which are small compared to gravity. Typical of the analytical works are those of Price (1970,1971) who attempted to perturb the solution for the wave of maximum amplitude and thereby to model the initiation of breaking. This approach was successful only in a qualitative sense and the mathematics are quite complex.

Cokelet (1977) has summarized most of the attempts to develop numerical techniques to study wave overturning and breaking prior to 1977. Many of the approaches were partially successful but, due to numerical difficulties of various sorts, had serious limitations in terms of representing steep, overturning waves. Other more recent attempts to develop numerical approaches are described by Kjeldsen, Vinje and Brevig (1980) and by Peregrine, Cokelet and McIver (1980).

In the keynote address at the 17th International Conference on Coastal Engineering Longuet-Higgins (1980) reviewed the work

which had been done until that time on the numerical and analytical modelling of wave breaking. He considered four sub-problems within the overall context of breaking waves. They were the limiting form of steep, symmetric waves; the form of steep, but not limiting, waves; overturning, time-dependent waves; and waves after breaking. The primary application was to coastal processes, but many of the general considerations apply equally well to deep water waves.

Longuet-Higgins and Cokelet (1976, 1978) developed an irrotational flow formulation for the numerical simulation of deep water surface wave overturning. In their formulation the physical flow domain is of infinite depth and the free surface is mapped onto a simple closed contour. For irrotational flow the shape of the fluid region boundary and the velocity potential on the boundary uniquely determine the flow field inside, so that primary attention can be given to accurately determining the boundary shape. Then the equations of fluid motion are solved in the transformed plane. The motion is assumed to be periodic in space in the direction of wave motion but not periodic in time. The transformed kinematic equations and Bernoulli's equation on the free surface then are solved to give the shape of the surface. The velocity potential ϕ over one wavelength is followed in time from one position of the free surface to succeeding locations after the imposition of appropriate initial conditions. The mapped free surface contour is divided into discrete elements and a matrix of simultaneous linear equations is solved for the normal gradient $\frac{\partial \phi}{\partial n}$ of the velocity potential on the boundary. Then the Bernoulli equation and the kinematic conditions on the boundary (three simultaneous linear differential equations in time) are integrated.

The accuracy of the solution is checked by calculating the total mass flux across the contour and the mean level of the water (both theoretically zero), and the sum of the kinetic and

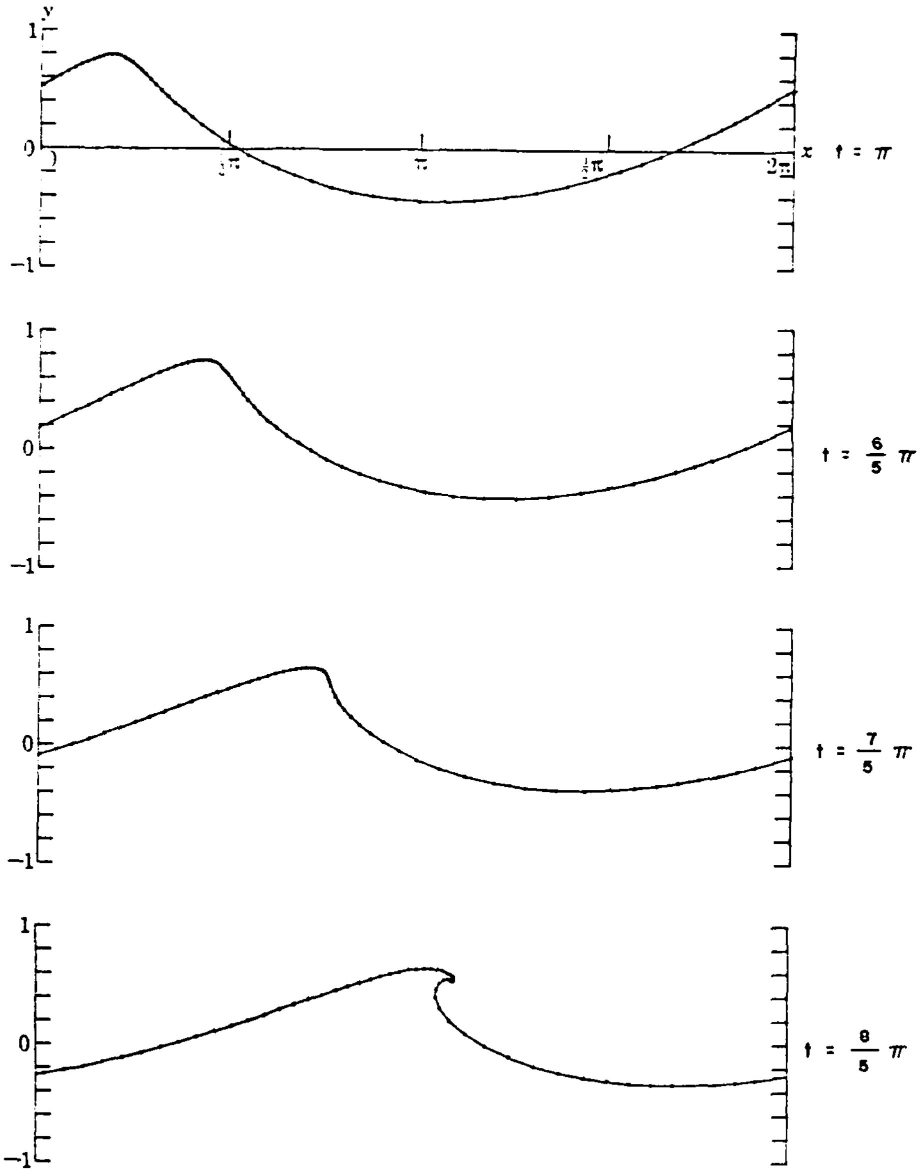
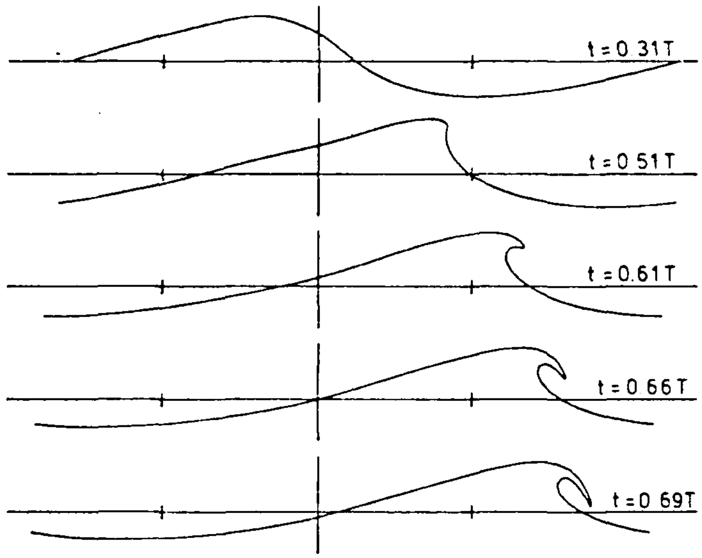


Figure 7 A numerical simulation of the overturning of a steep wave in deep water; from Longuet-Higgins and Cokelet (1976).

potential energies (constant when there is no input of energy by pressure action at the boundary surface). An example of an overturning deep water wave taken from the results of Longuet-Higgins and Cokelet is shown in Figure 7. For the sequence shown the wave is free running. Prior to the normalized time $t = \pi$ a sinusoidally varying pressure disturbance (in space and time) with a (normalized) amplitude $p_o = 0.146$ was applied to the free surface. The pressure disturbance progressed at the same rate as an infinitesimal deep water wave. The overhanging wave crest is typical of the results obtained by Longuet-Higgins and Cokelet. The method developed by them for travelling free surface waves has been extended by Srokosz (1981) to the simulation of standing waves and partially-reflected waves.

A numerical method similar to that of Longuet-Higgins and Cokelet has been described by Kjeldsen, Vinje and Brevig (1980) and by Vinje and Brevig (1980, 1981a, 1981b). In this latter method the fluid depth is finite and the computations are carried out in the physical plane instead of the transformed plane. The solution is obtained by dividing the contour surrounding the computational domain into discrete elements and then applying the weighted residual method to solve the governing integral equation for the complex velocity potential. Then the complex Bernoulli equation and the kinematic equations at the free surface are integrated in time. A time history of the development of a deep-water plunging breaker from a sinusoidal wave, computed by Vinje and Brevig (1981b), is shown in Figure 8.

A comparison of the two numerical schemes has been made by McIver and Peregrine (1981). Comparable results were obtained with both approaches for a fluid domain approaching infinite depth, and the difficulties involved in achieving sufficient numerical resolution were clearly evident in both cases. Both methods are capable of simulating the motion of a plunging



Deep-water wave.

Figure 8 A numerical simulation of the time development of a plunging breaker in deep water; from Vinje and Brevig (1980).

breaker beyond the time when the forward face of the wave becomes vertical and to later times when an overhanging jet is formed.

The numerical method described by Longuet-Higgins and Cokelet (1976) was also used to conduct a study of the growth and decay of the normal mode instabilities of steep surface gravity waves (Longuet-Higgins and Cokelet, 1978). The purpose of the study was to verify and extend the normal mode analysis of Longuet-Higgins (1978a, 1978b). The calculations reported by Longuet-Higgins were lengthy and complicated, and led to some unexpected conclusions. It was found that two distinct types of instabilities were present: first, subharmonic instabilities of the Benjamin-Feir type, of longer wavelength than the basic wave, which were confined to waves with steepness less than ak = 0.37; second, superharmonic instabilities that appeared when ak = 0.41. These disturbances had large growth rates which were suggested by Longuet-Higgins (1978a) to lead directly to wave breaking.

The normal mode stability analysis of Longuet-Higgins is limited to small perturbations of the finite-amplitude waves, whereas the numerical method of Longuet-Higgins and Cokelet is not. The numerical calculations can be carried to the point where both the basic wave and the perturbations of it are of finite amplitude. The previous calculations of Longuet-Higgins (1978a,b) were confirmed for wave steepnesses in the range $0.1 \leq ak \leq 0.41$. For ak = 0.1 and 0.2 the waves were stable, while for ak = 0.25 and 0.32 the waves were unstable. When ak = 0.38 and 0.40 the waves again were stable, but at ak = 0.41 the waves became violently unstable. The growth rates of the perturbations computed with the time-stepping method at these wave steepnesses are plotted in Figure 9 together with the previous results of Longuet-Higgins (1978a). The results of the two approaches are in good agreement. In all of these cases the

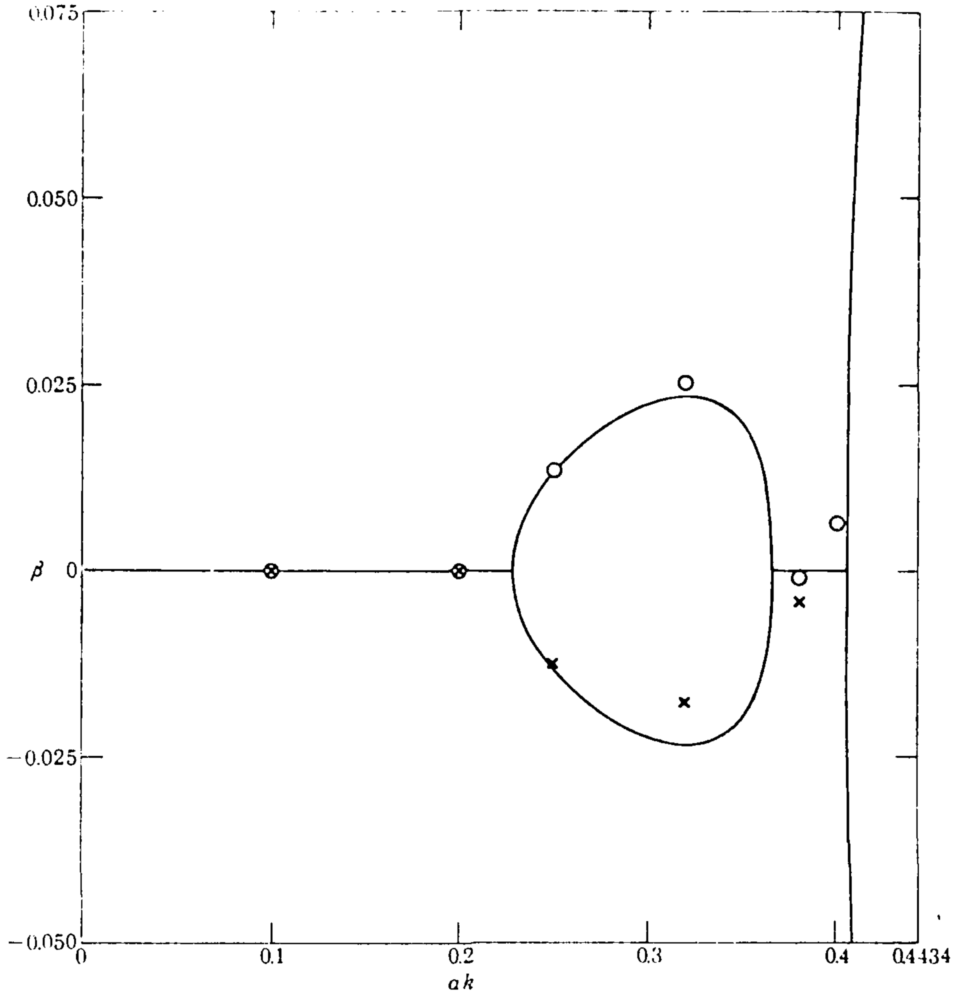


Figure 9 The linear growth rate β of perturbations of steep waves as a function of the wave number ak. The curves represent the calculations of Longuet-Higgins (1978a); the individual points were computed by Longuet-Higgins and Cokelet (1978).

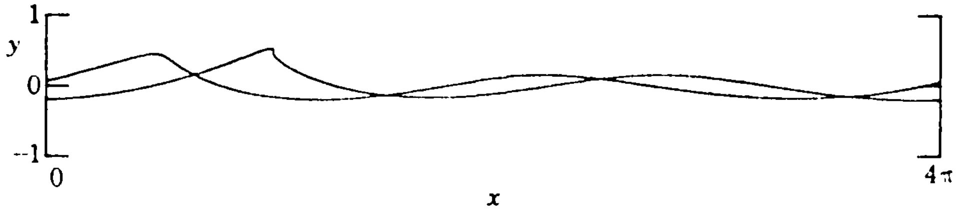


Figure 10 Profiles of an unstable mode for the overturning of a steep gravity wave with ak = 0.25. The normalized time interval between the profiles is $\Delta t = 2\pi/4$; from Longuet-Higgins and Cokelet (1978).

waves were free running since no pressure perturbation was applied at the free surface to add energy to the flow field.

Two wave profiles near the breaking point when ak = 0.25 are shown in Figure 10. The results were obtained at two relatively late (normalized) times in the computation. Alternate waves appear to be increased in amplitude and reduced in wavelength, and they break due to the presence of subharmonic instabilities when the <u>local</u> steepness is larger than $ak \cong 0.30$. The final stages of the approach to breaking computed by Longuet-Higgins and Cokelet (1978) appear to be similar for all of the cases investigated. The local wave dynamics appeared to be related to local scales of length and time near the crest of the breaker. It was hoped that these characteristics of the flow field might lead to a unified nonlinear theory of wave breaking in the future.

Some additional studies of the plunging breaker have been conducted using the time-stepping method of Longuet-Higgins and Cokelet. Cokelet (1979) showed that the interior velocity and acceleration fields for the irrotational waves could be obtained from quantities evaluated at the free surface. Peregrine, Cokelet and McIver (1980) found certain properties that were thought to be characteristic of a wave approaching breaking. These are:

- o Particle velocities greater than the local phase velocity near the wave crest;
- o Particle accelerations greater than gravity on the forward face of the wave;
- o Particle accelerations well less than gravity on the face of the wave behind the crest.

The development of these regions in time is shown in Figure 11. The sequence of the wave motion was computed using the method of Longuet-Higgins and Cokelet with an initial pressure amplitude of $p_o = 0.146$ to initiate the deep water

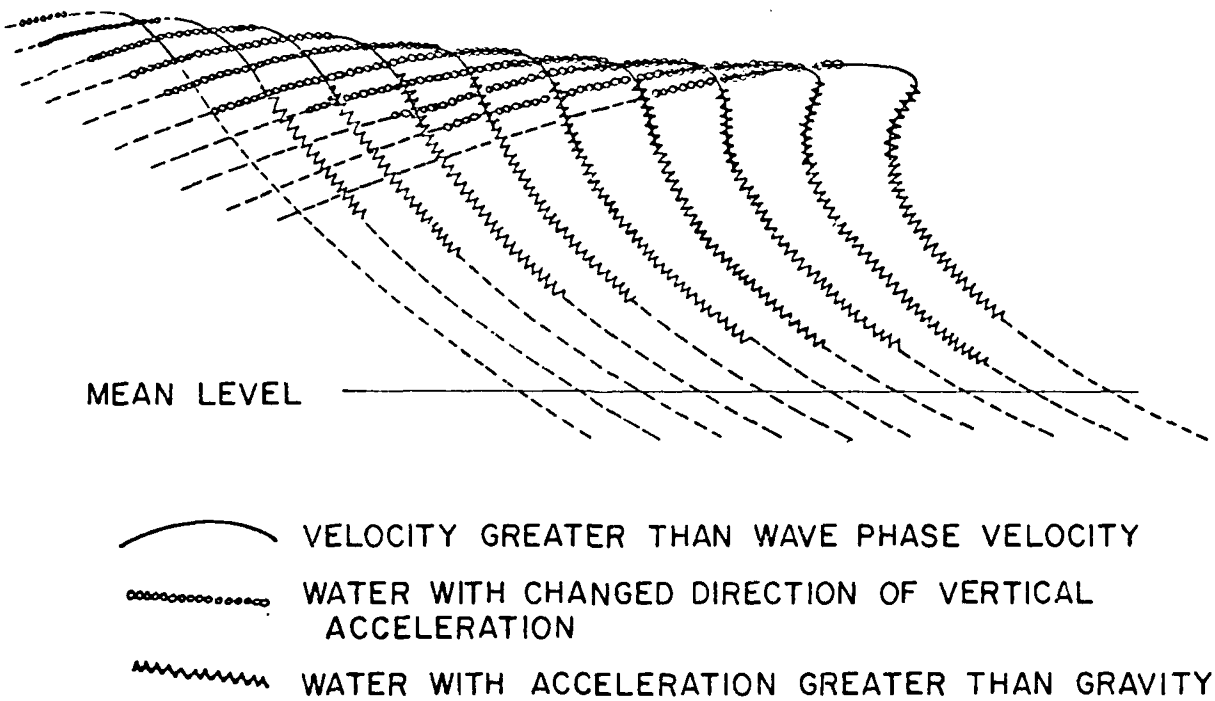


Figure 11 Properties of a wave approaching breaking; from Peregrine, Cokelet and McIver (1980). The normalized times range from $37\pi/30 \leq t \leq 46\pi/30$; the initial pressure amplitude $p_o = 0.146$.

overturning wave. There is a broad region of high acceleration for the fluid particles on the forward face of the overturning wave. This case also was discussed previously in this report. These features were not thought to be characteristic of deep water waves in general, but only to the two-dimensional plunging breaker.

The initial findings from a numerical study of the effects of intermediate and deepwater wave breaking over submerged obstacles has been described by Fritts (1982). The approach is based upon a Lagrangian, finite-difference computer code which employs a triangular mesh. This code previously was used by Miner et al (1983) to simulate the flow of non-breaking waves over submerged cylindrical obstacles. In that study good agreement was obtained under certain conditions between the numerical results and experiments conducted in a laboratory wave channel. The computer code employed by Fritts is limited to periodic boundary conditions at the upstream and downstream extremities of the computational domain. Consequently this limits the computer simulation to low values of wave reflection from the obstacle, i.e. the ratio R of the reflected and incident wave amplitudes should be less than R = 0.1 to 0.15, as shown by Miner et al (1983).

McLean et al (1981) have undertaken a numerical study of the stability of the full deep-water wave equations to linear three-dimensional disturbances. Two types of instabilities were found. The so-called Type I instability is predominantly two-dimensional and includes the Benjamin-Feir instability as a special case. This instability has the larger growth rate for $ak<0.28$. The Type II instability is three-dimensional and is dominant at wave steepnesses larger than $ak=0.28$. The largest growth rates of the Type II instability were found at $p=0.5$, where p is the ratio of the longitudinal disturbance and primary wave numbers. The growth rate increases with increasing wave

steepness. Melville (1982) and Su et al (1982) obtained good agreement between the normalized transverse wavenumber q measured in a wave channel and the computations of McLean et al for Type II disturbances at p=0.5 and ak ≈ 0.3. Melville also found the disturbance and the primary waves to be co-propagating at the primary wave phase velocity as had been predicted by McLean et al (1981).

A numerical method for computing the motions of incompressible, inviscid, irrotational flows with a free surface has been developed by Baker, Meiron and Orszag (1982). The method is based upon the evolution equations for the position of the free surface and the dipole and source strengths. Again the computational domain is somewhat limited by periodic boundary conditions at its upstream and downstream ends. A formulation similar to that of Longuet-Higgins and Cokelet (1976) was used to initiate the approach to breaking of a steep wave in deep water. A moving pressure pulse was applied initially over part of the computation, after which the wave ran free. The wave overturned and a jet of fluid was ejected from the forward face of the wave. The method converged until the curvature at the tip became too great to resolve with a practical number of grid points. This same limiting factor on the convergence was observed by Vinje and Brevig (1981), and by McIver and Peregrine (1981).

Longuet-Higgins and Fox (1978) have studied the properties of steep gravity waves in deep water. The objective of the study was to derive, in as simple a manner as possible, the properties of steep waves. An inner solution valid near the crest was found and matched to an 'outer flow' that encompassed the rest of the wave. A matching parameter

$$\varepsilon = \frac{q_c}{c_o\sqrt{2}} \tag{3.1}$$

was derived. Here q_c is the particle speed at the crest and $c_o = (g/k)^{1/2}$ is the speed of infinitesimal waves in deep water. The expansion parameter ε is defined in such a way that the vertical displacement $\overline{y}_c$ of the crest from the mean water level is given by

$$\overline{y}_c \sim \varepsilon^2 .$$

Asymptotic expressions were found for the wave speed, the wave height, and the potential and kinetic energies for the steep waves. The expression

$$c^2 = c_o^2 \left[1.19 - 1.18 \varepsilon^3 \cos (2.14 \ln \varepsilon + 2.2) \right] \tag{3.2}$$

was obtained for the wave speed. This was found to be a reasonable approximation for values of the parameter

$$\omega' = 1 - \frac{2 \varepsilon^2 q_t^2}{c_o^2} > 0.6, \tag{3.3}$$

corresponding to steep waves. Here q_t is the fluid particle speed in the wave trough. The wave steepness ak is given by the expression

$$ka = 0.141\pi - 0.50 \varepsilon^2 + 0.160\pi \varepsilon^3 (2.14 \ln \varepsilon - 1.54). \tag{3.4}$$

Various integral properties of a steep wave were derived in a similar manner. The normalized potential energy V per unit area is

$$V = (c_o^2/k) \left[0.0346 - 0.169 \varepsilon^3 \cos (2.14 \ln \varepsilon + 1.49) \right] \tag{3.5}$$

and the corresponding kinetic energy T is

$$T = \left(c_o^2/k\right)\left[0.0383 - 0.215\,\varepsilon^3 \cos\left(2.14 \ln \varepsilon + 1.66\right)\right]. \quad (3.6)$$

These expressions may prove useful later in deriving onset criteria and an empirical model for the breaking of waves in deep water.

Longuet-Higgins (1982) has derived a parametric model for predicting certain features of waves that are approaching breaking. It was found that a certain class of self-similar solutions could be employed to simulate certain stages in the development of an overturning wave. One such solution, superimposed over the wave shown in Figure 3, is shown in Figure 12. The calculated shape of the forward face of the wave closely models the real plunging breaker shown in the photograph. Longuet-Higgins also obtained good agreement between predictions of the shape of the wave's forward face using his parametric model and similar numerical predictions by Vinje and Brevig (1981) of the temporal development of a plunging breaker in deep water.

Both New (1983) and Greenhow (1983) have extended the analytical approach taken by Longuet-Higgins. New demonstrated clearly that a certain class of ellipse (with aspect ratio equal to $\sqrt{3}$) could closely model the essential features of a numerical representation of the overturning wave. The numerical model was an extension of the original work of Longuet-Higgins and Cokelet (1976). This class of ellipse also closely fitted the shape of a laboratory-generated plunging breaker (Miller, 1976) at the late stages of breaking. Greenhow (1983) extended this analytical approach still further. One drawback of the initial work of Longuet-Higgins and New is the limitation of the fitted profile to only a segment of the forward face of the wave. Greenhow has shown how a mathematical formulation developed to represent the jet of fluid ejected from the forward face of the wave (Longuet-Higgins, 1980) can be combined with

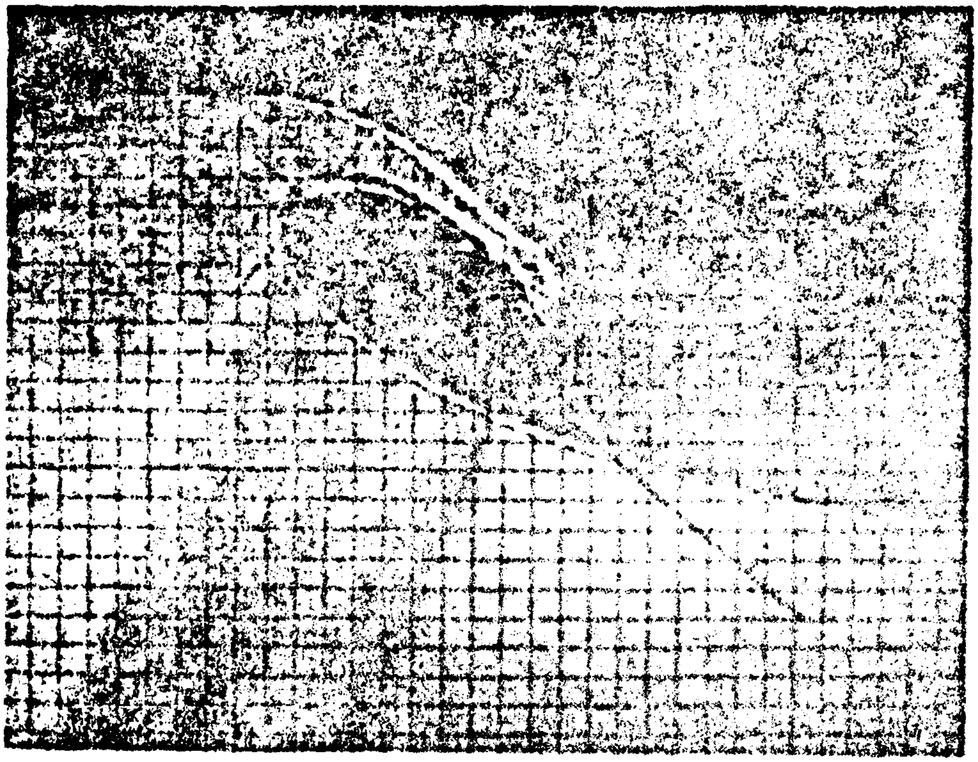


Figure 12 A comparison of a self-similar analytic approximation of an overturning gravity wave with the observed profile in Figure 3; from Longuet-Higgins (1982).

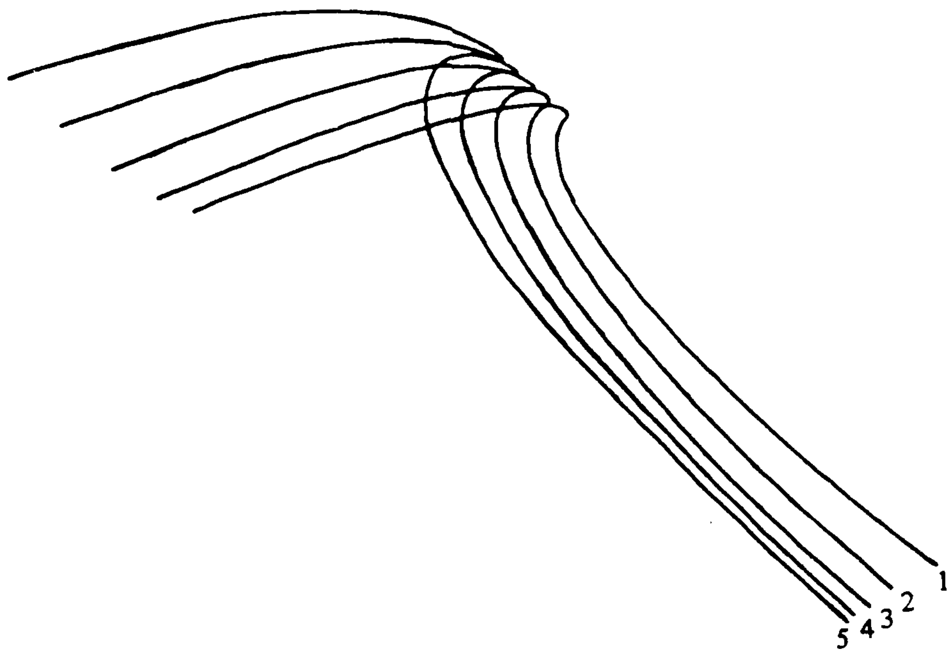


Figure 13 A computed time history of the development of a spilling breaker; from Greenhow (1983).

the ellipse model of New. The two solutions are complementary at large times and give a more complete model of the entire overturning region near the wave crest. An example of the development in time of the profile of a spilling breaker is given in Figure 13. The wave profiles shown there give a reasonable representation of the incipient stages of the breaker. Qualitative agreement also was obtained with a numerical simulation of a plunging breaker based upon the model of Vinje and Brevig (1981a, 1981b). A drawback common to all three approaches is that the effects of gravity are taken into account only in an approximate way.

4. AIR ENTRAINMENT

If air is mixed in sufficient quantity with a liquid which has the appropriate properties, then a foam often will form (Hubbard and Griffin, 1984). Mechanical agitation is one method for mixing air in a liquid. The flow in a breaking wave is probably a type of agitation which is suitable for foam formation. The downstream wake of a surface vessel also is characterized by a layer of foamy, agitated water near the surface. A classic study of ship wakes and white water dating from the years during and just after World War Two is given in a U.S. Navy report compiled by the National Defense Research Council (1969).

Fuhrboter (1970) has studied specifically the air entrainment process for breaking waves in shallow water. From a brief study it was concluded that the wave energy in a plunging breaker was dissipated over a distance less than one wavelength long. The distance over which the energy was dissipated in a spilling breaker was several wavelengths long. However, this study was quite limited in scope.

This topic also has been discussed by Longuet-Higgins and

Turner (1974) in the development of their entraining plume model of spilling breaker. Much of the literature relevant to white water formation from the years prior to 1974 is reviewed by Longuet-Higgins and Turner. The available information for the most part had been obtained in studies of the flow in hydraulic jumps. Madsen and Svendsen (1983) have recently updated this review.

Peregrine and Svendsen (1978) have proposed a somewhat different model for the turbulent flow and white water region of a spilling breaker. After assuming that the breaking process is quasi-steady, they then cite several similarities between the turbulent region of the breaker and the classical flow field of the turbulent mixing layer. The observations made by Peregrine and Svendsen have been used by Madsen and Svendsen (1983) as the basis for a theoretical model for the velocity fields and surface profiles of bores and hydraulic jumps. The method potentially is applicable to modeling the toe region of a turbulent breaker in deep water.

Mixing air and water by means of plunging jets and by the action of turbulent eddies in water flowing over spillways has been discussed by many authors. This work is discussed by Hubbard and Griffin (1984) in relation to its potential value in the hydrodynamic modeling of the air entrainment and white water production processes in breaking waves.

In the entraining plume model of Longuet-Higgins and Turner (1974) three basic mechanisms for entraining air were considered to be relevant to the generation of white water in breaking waves. The first is the over-running of a layer of air by the advancing breaker. The maximum concentration of air is approximately 20 percent; this yields a mean density of the mixture equal to about 80 percent of the underlying water density.

Another mechanism is the so-called 'self-aeration' that takes place in the upper layer of a rapidly moving turbulent flow with a free surface. An open channel flow, for instance, begins to entrain the nearby air when the turbulent boundary layer on the channel bottom reaches the surface and white water begins to develop. In this case the equilibrium distribution of air shows a continuous variation from water containing few air bubbles on the bottom to all air and no water at the top. There are essentially two layers, the lower a mixture of air bubbles suspended in water and the upper a mixture of water droplets in air. The mean density and the density of the bottom layer depend strongly on the slope of the channel, and weakly on the Froude number of the flow. This mechanism would seem to have limited applicability to deep water waves.

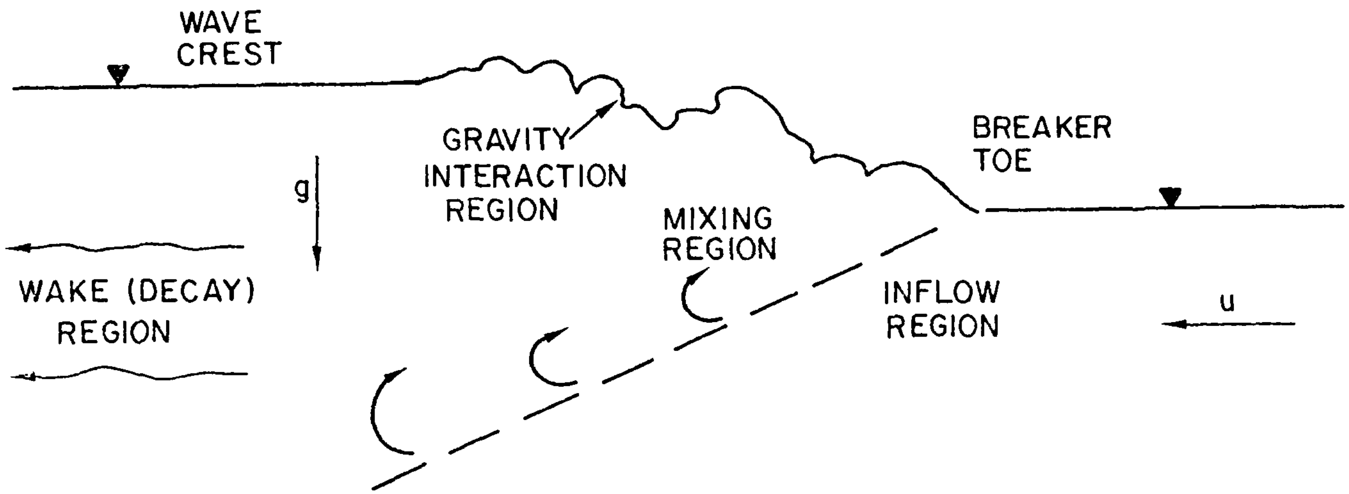
The third mechanism concerns the relative balance between the turbulent energy and the energy contribution due to surface tension. Entrainment can only occur when the turbulent flow at the free surface is energetic enough to overcome the surface tension and to entrain the nearby air. A criterion has been proposed by Gangadharaiah et al (1970) such that the 'entrainment number' I is greater than a critical value, or

$$I = (\rho h \bar{U}^2 / \sigma)\ (u_* h/\nu)^{1/2} > I_c . \tag{4.11}$$

In this expression h is the depth, $\bar{U}$ a mean velocity, u_* the friction velocity, σ the surface tension and ν the kinematic viscosity. Longuet-Higgins and Turner (1974) have estimated I_c to be of order 50 before air entrainment begins at the free surface. This criterion is thought to apply to the later stages of the spilling breaker development; at the early stages over-running at the forward region of the breaker is the primary means of air entrainment.

The quasi-steady mixing layer model of Peregrine and Svendsen (1978) is somewhat less heuristic (in principle) and potentially more appealing in terms of applications to spilling breakers in deep water. The essentials of the flow field as envisioned by them are sketched in Figure 14 for the deep water case. The velocity of the upper fluid stream (air in this case) is assumed to be zero or a very small quantity. There is a gravity-dominated region near the wave crest, and a mixing region which increases linearly in thickness downstream from the toe region of the breaker. A wake region then extends downstream for some distance where the turbulence penetrates and dissipates. According to Peregrine and Svendsen, air entrainment is likely to be important in the early part of the wake near the toe of the breaker. Downstream air entrainment effects are expected to be of lesser importance. Duncan (1981) found that the wake thickness downstream from a steady breaker varied as $(\text{distance})^{1/2}$ and this point should be clarified vis a vis the mixing layer model. Madsen and Svendsen (1983) have compared calculations of the turbulent layer thickness downstream from a steady hydraulic jump with measurements from several sources (including their own data). The results appear to confirm Duncan's measurements to some extent since the layer thickness increase with distance from the toe of the jump definitely is of the form $(\text{distance})^n$ where $n < 1$.

It is clear from the preceding discussion that relatively little is known quantitatively about the processes of turbulence and air entrainment in breaking waves. Various arguments have been made to apply the results obtained from studying other physically similar flows to this problem, but the path to a well-ordered model is by no means clear. A more complete knowledge of the these processes will play an important role in the further development of plausible models for microwave radar scattering from breaking waves (Wetzel, 1981).



(COORDINATES MOVING WITH THE WAVE)

Figure 14 Model of a quasi-steady breaking wave on deep water; adapted from Peregrine and Svendsen (1978).

5. ONSET CRITERIA FOR WAVE BREAKING

It is possible on the basis of both recent and earlier studies to suggest certain criteria for wave breaking under limited conditions. Most of the available evidence is qualitative in nature. There are only limited quantitative data to aid in developing criteria for breaking. The available results are summarized here for deep water waves and then briefly for intermediate and shallow water waves, or waves on beaches. Several special cases also are considered. These include wave breaking over submerged obstacles, waves in wind and current fields, and steady breaking waves. The wave breaking inception criteria which were derived prior to 1978 are summarized in Table 1, from Kjeldsen and Myrhaug (1978). Some of these and other more recently-derived criteria are discussed here.

Deep Water Waves. What is known concerning onset criteria for deep water wave breaking can be found in the recent work of Kjeldsen et al (1978,1979,1980), Melville (1982), and Su et al (1982).

In order to classify the breaking waves Kjeldsen et al introduced several non-dimensional wave steepness parameters. The most important was thought to be the so-called "crest front steepness", or

$$\varepsilon = \frac{a'}{\lambda'}$$

where a' is the vertical distance from the mean water level to the wave crest and λ' is the horizontal distance from the zero upcross point on the wave to the wave crest. The crest front steepness was considered to be more representative of the asymmetric profile of an overturning wave, as compared to the more usual wave steepness

Table 1 Theoretical Breaking Criteria for Gravity Waves in Deep and Shallow Water; from Kjeldsen and Myrhaug (1978)

CONDITION	STATE		SYMMETRY		ACTION OF WIND		DEEP WATER	SHALLOW WATER	CRITERIA	Reference†
	Steady	Unsteady	Symmetric	Asymmetric	Yes	No				
GEOMETRICAL	X		X			X	X		1. The angle at the top of the crest becomes 120 degrees.	STOKES 1880
	X	(X)	X	(X)		X	X		2. The steepness $s=2a/\lambda$ reaches a limiting value near 0.142.	MICHELL 1893
		X		X		X	X	X	3. The front face of the wave becomes vertical.	-
	X	X	X	X		X		X	4. $H/d = 0.78$	McCOWAN 1891
KINEMATIC		X		X		X	X	X	5. The horizontal particle velocity at the surface exceeds the phase velocity $u > c$.	-
		X		X	X		X	X	6. $a_{max} = \frac{c^2}{2g}(1 - \frac{q}{c})^2$ q - surface drift	BANNER & PHILLIPS 1974
DYNAMIC	X		X			X	X		7. The downward acceleration in the wave crest exceeds $\frac{1}{2}g$.	LONGUET-HIGGINS 1969
		X		X		X	X	X	8. The vertical upward acceleration in the wave crest exceeds g or $\frac{Dw}{Dt} < -\frac{1}{\rho}\frac{\partial p}{\partial z} + g$. No vertical momentum flux	SMITH 1976

†From Kjeldsen and Myrhaug (1978).

$$s = \pi^{-1}(ak) \ . \tag{5.1}$$

This is because many extreme waves of the same steepness s can have different wave crest steepnesses. Typical values of ε for the breaking wave experiments of Kjeldsen et al were in the range

$$0.32 < \varepsilon < 0.78.$$

The highest values corresponded to plunging breakers, while spilling breakers were of lower steepnesses.

As noted earlier, Melville (1982) studied the breaking of deep water waves in a laboratory wave channel. The wave steepnesses were in the range $0.15 < ak < 0.35$. For $ak < 0.3$ the evolution of the waves to breaking was essentially two-dimensional with the Benjamin-Feir instability leading directly to breaking. The side-band instabilities predicted by Benjamin and Feir grow asymmetrically and ultimately the wave frequency shifts to the lower value. Measurements by Melville of the modulation frequency agreed well with the predictions of Longuet-Higgins (1980) as shown in Figure 15. The agreement of Melville's measurements with the prediction based upon Benjamin and Feir's theory (1967) is not quite so good.

The profiles of the breaking waves photographed by Melville at $ak < 0.3$ show considerable agreement with the numerical solution of Longuet-Higgins and Cokelet (1978). An example from the latter is shown here in Figure 10. On the bas' of this agreement it was suggested by Melville (1982) that the numerical simulations of Longuet-Higgins and Cokelet and those of Vinje and Brevig (1981a,b) can be used to interpret not only the wave motion before breaking but also the wave motion in the breaking region.

When $ak > 0.31$ Melville found that three-dimensional effects appeared to dominate the Benjamin-Feir instability. Two examples at $ak = 0.315$ and 0.321 are shown here in Figure 2. The perturbations were crescent-shaped spilling breakers and appeared to be phase-locked to the speed of the basic wave. These three-dimensional disturbances were associated with the so-called Type II disturbances of McLean et al (1981). The maximum instability always occurs for $p = 0.5$ and $q = 0$, where p and q respectively, are the ratios of the longitudinal and transverse wavenumbers to the basic wavenumber. A number of predicted and measured values of ak and q are plotted in Figure 16. The predictions were made by McLean et al (1981), Saffman and Yuen (1981), and Longuet-Higgins (1978b). The latter is the limiting case for $q=0$ or infinite wavelength of the transverse perturbation (flow in two dimensions). The measurements were made by Melville (1982) and Su et al (1982).

McLean et al had found that the evolution of a deep water wave train was two dimensional for $ak < 0.29$ (Type I disturbances) and three-dimensional (Type II) for larger values of ak. This is in agreement with the experimental findings of Melville (1982).

The laboratory experiments of Su et al (1982) were conducted with initially two-dimensional steep wave trains with $ak = 0.25$ to 0.34. It was found that two-dimensional wave trains in this range of steepnesses were unstable to both two-dimensional and three-dimensional subharmonic instabilities. The wave forms are essentially two-dimensional in the early stages of the modulation. Then the growth of transverse perturbations causes a three-dimensional structure. Then the wave train develops rapidly into rows of crescent-shaped breakers which resemble spilling breakers in the open ocean.

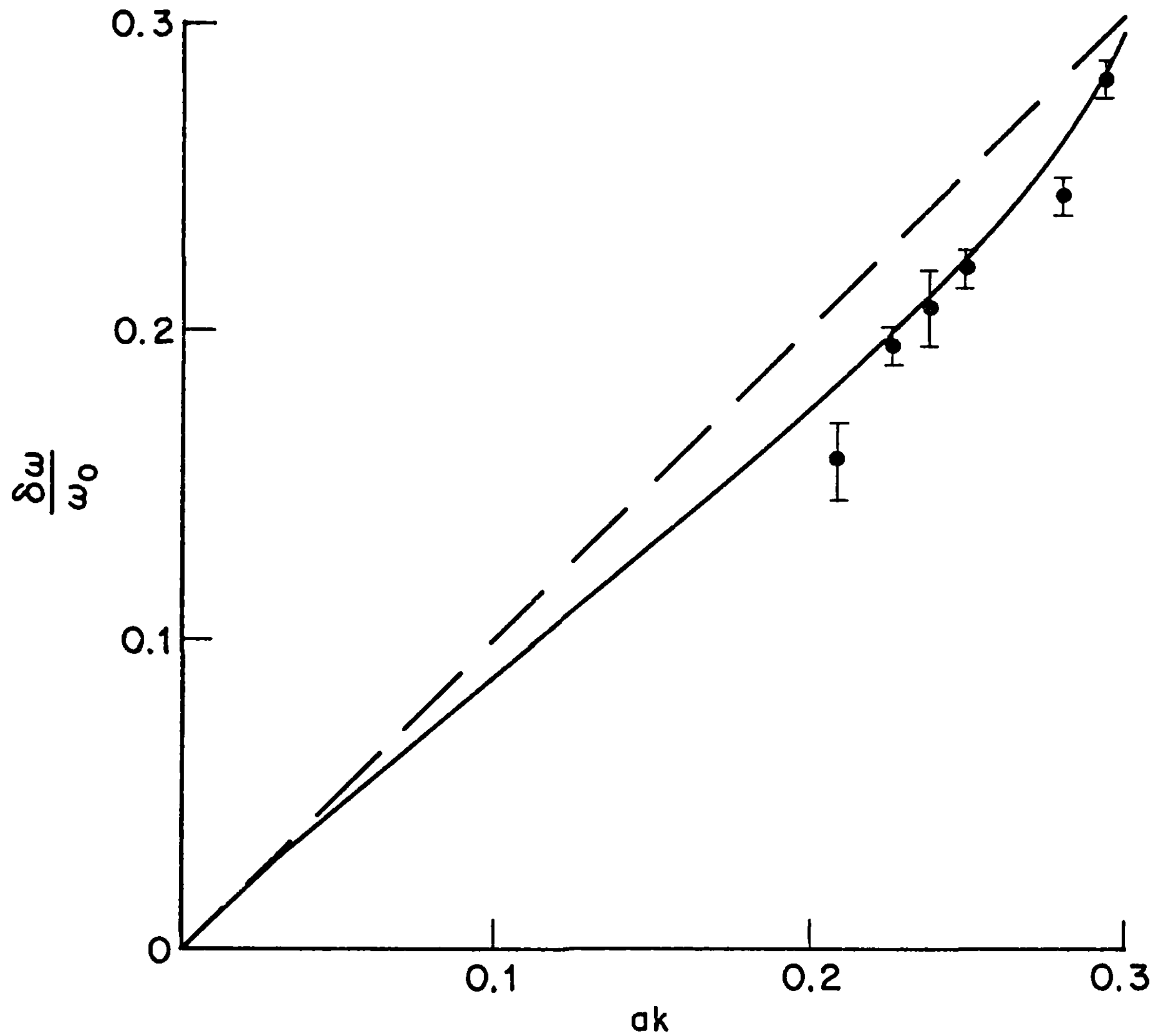


Figure 15 Normalized wave modulation frequency $\delta\omega/\omega$ as a function of the wave steepness ak; adapted from Melville (1982). ●, measured values from Melville (1982; ———, Longuet-Higgins (1980); - - -, Benjamin and Feir (1967).

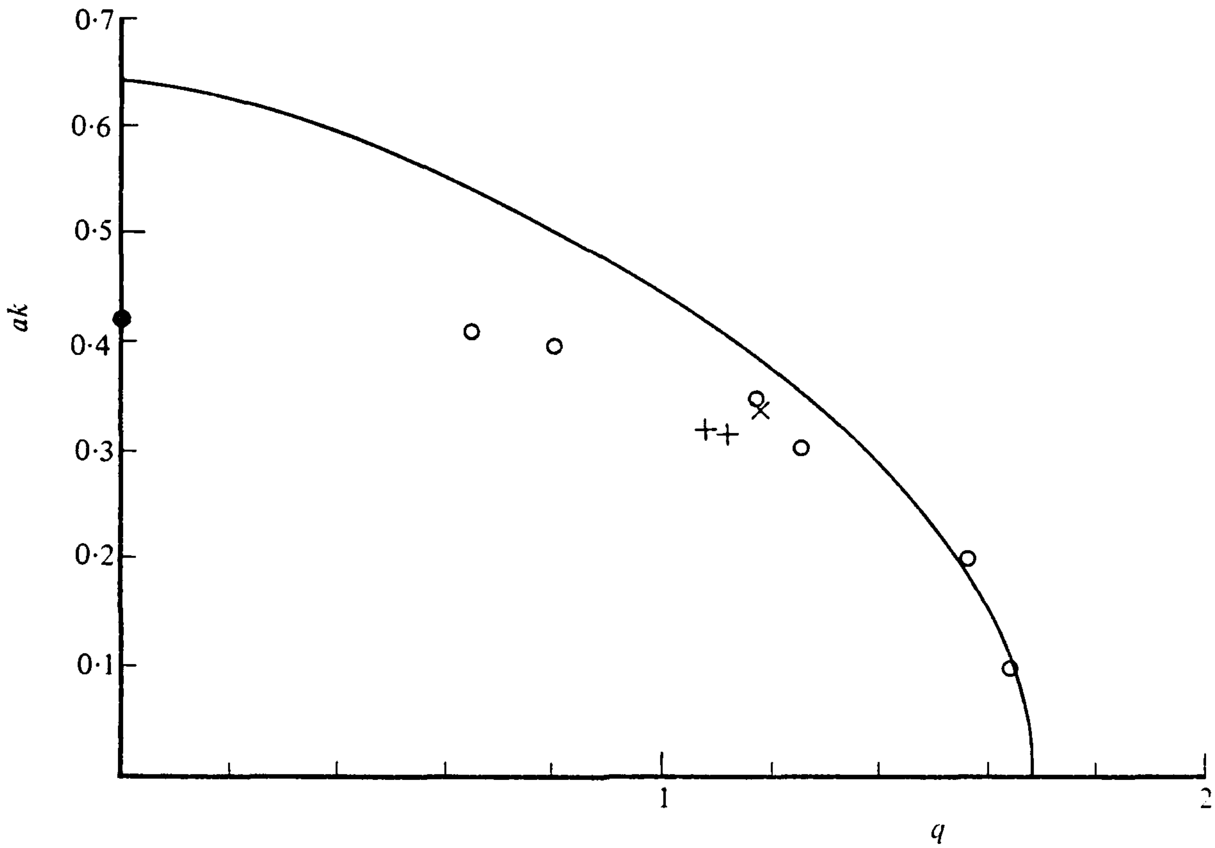


Figure 16 Normalized transverse wavenumber q of the most unstable subharmonic perturbation, for a normalized longitudinal wavenumber p = 0.5; from Melville (1982). ———— , prediction of Saffman and Yuen (1981); 0, McLean et al (1981); x, Su et al (1982); +, Melville (1982); ●, Longuet-Higgins (1978b).

These three-dimensional breakers transform back to long crested wave forms. The waves further evolve into modulated groups with lower steepness and lower frequency. The frequency is downshifted by as much as 25 percent. Su et al observed essentially the same phenomena in a long, narrow laboratory channel and in an outdoor wave basin. Reasonably good, but limited, agreement was found between the measurements of Su et al at $ak = 0.33$, the measurements of Melville (1982) at $ak \approx 0.31$, and the numerical results of McLean et al (1981) as shown in Figure 16.

Su et al also obtained good qualitative agreement with the stability analysis of Longuet-Higgins (1978b) in terms of the appearance of subharmonic instabilities. However, the work of Longuet-Higgins is predicated upon the overturning wave evolving into a two-dimensional plunging breaker, whereas the breakers observed by Su et al were three-dimensional spilling breakers. It was thought that the predominant factor at the large wave steepnesses ($ak > 0.3$) was the appearance of the Type II instabilities of McLean et al (1981). Based upon the available evidence it is not possible to do more than bound the wave evolution process as shown in Table 2. In all cases the wave breaking was initiated at wave steepnesses well below the steady limiting steepness of $ak = 0.443$.

A criterion for the onset of wave breaking can be derived from the results obtained by Melville (1982), Su et al (1982), and McLean et al (1981). The criterion is of a form proposed by Nath and Ramsey (1974, 1976) and which was then evaluated based upon Dean's stream-function wave theory. The criterion is of the form

$$H_b = \sigma \ T_b^2 \qquad (5.2)$$

where H_b is the wave height when breaking occurs; T_b is the corresponding period for the breaking wave; and σ is a "breaking

coefficient". The value of σ derived by Nath and Ramsey was $\sigma = 0.875\ ft/sec^2$ ($0.267\ m/sec^2$), which is based also upon the "steepest" wave of $ak = 0.443$.

Table 2

Wave Breaking in Deep Water

Wave Steepness	Type of Instability	Breaker Type
$0.15 < ak < 0.3$	Two-dimensional; Benjamin and Feir (1967), McLean et al (1981), Longuet Higgins and Cokelet (1978).	Spilling, Plunging
$ak \geq 0.3$	Three dimensional; McLean et al (1981), Melville (1982), Su et al (1982).	Spilling

Consider the limiting wave steepness condition above which three-dimensional spilling breakers evolve naturally,

$$ak = 0.3,$$

which follows from the wave channel experiments of Melville and Su et al. To a first-order approximation the incident wave amplitude a is related to the breaking wave height H_b by

$$H_b = 2a^{+}.$$

Then

$$H_b = \frac{0.6\ \lambda_b}{2\pi} \qquad (5.3)$$

since $k = 2\pi/\lambda$. For linear deep water waves as an additional approximation

+This amplitude refers to the initial amplitude of the unbreaking wave train.

$$\lambda = \frac{gT^2}{2\pi}, \tag{5.4}$$

so that

$$H_b = \frac{0.6g}{(2\pi)^2} T_b^2 \tag{5.5}$$

for a wave that spills naturally. For $g = 32.2$ ft/sec^2 (9.8 m/s^2) the coefficient σ is

$$\sigma_{MS} = 0.49 \text{ ft/sec}^2 \quad (0.15 \text{ m/s}^2)$$

which can be called the Melville-Su breaking coefficient.

A second-order correction to σ_{MS} increases it from 0.49 to 0.53. For deep water waves the second-order correction to the phase velocity is, after Stokes (1932),

$$c_*^2 = g/k_*(1+a^2 k^2), \tag{5.6}$$

so that

$$\lambda_* = \frac{g t_*^2}{2\pi} (1+a^2 k^2). \tag{5.7}$$

When Eq. (5.5) is corrected in this way, the new breaking coefficient is $\sigma_{MS} = 0.5$ ft/sec^2(0.16m/sec^2). If σ is based upon Stokes' limiting wave steepness of $ak = 0.443$, then σ is increased to $\sigma_{MS} = 0.86$ ft/sec^2(0.26m/sec^2), correct to second order. This value is just about equal to the one derived by Nath and Ramsey.

These are somewhat more conservative estimates of σ than the value derived by Nath and Ramsey. However, the values for σ derived here are based upon the most recent laboratory-scale observations of the onset of spilling for breakers in deep water. More sophisticated higher-order modifications to the breaking criterion possibly could better take into account the finite wave steepness. The breaking coefficient and wave forecasting model derived by Nath and Ramsey were employed by

Kjeldsen and Myrhaug (1978) in their development of a probabilistic model to forecast the occurrence of breaking waves in deep water. The first steps toward the development of such a model had been taken also by Nath and Ramsey. This model is discussed in the next chapter of this report.

Van Dorn and Pazan (1975) conducted a systematic laboratory study of deep water wave breaking. A converging section was installed inside a wave channel to increase the steepness of the wave train. When the wave steepness was less than $ak = 0.3$ the wave profiles remained approximately symmetric and Stokes' fifth-order wave theory gave a good description of the wave properties. This was called the "young" wave regime. For wave steepnesses between $0.3 < ak < 0.38$ the wave profiles became increasingly asymmetric with a steep forward face. Most of the change in the profile was confined to that portion of the wave above the still water level. The rate of increase of potential energy density along the channel before breaking was inversely proportional to the channel width. Thus the energy flux was conserved. This was called the "pre-breaking" regime.

Wave breaking occurred spontaneously when $0.38 < ak < 0.44$. The forward face of the wave became nearly vertical and a jet of water issued from the forward face just below the crest. This appears to be similar in character to the overturning process which precedes the plunging of a breaker. The maximum jet velocity approached the limiting value $c_{L/M} = 1.2\ g/\omega$ for Stokes waves of maximum height. This was called the "breaking" regime by Van Dorn and Pazan. The three regimes just discussed are shown in Figure 17. Table 3 summarizes the characteristics of the three wave regimes.

The wave steepnesses at breaking in Table 3 are somewhat higher than those observed by Melville (1982), Su et al (1982), and by Duncan (1983). The converging walls of the channel may

have stabilized the wave motion as compared to the wave motion in a uniform channel. The plunging character of the wave breaking observed by Van Dorn and Pazan may be due to the constraining effect of the converging channel. Most other observations of deep water wave breaking have been in the form of spilling breakers. The results of an analogous study which was conducted with breaking waves in shallow and intermediate depth water has been reported by Van Dorn (1978).

Table 3

Deep Water Wave Breaking in a Converging Channel+

Wave Steepness	Wave Characteristics
$ak<0.3$	"Young" waves-symmetric about the crest; Stokes' fifth-order theory applies.
$0.3<ak<0.38$	"Pre-breaking" waves-asymmetric waves with steep forward faces; streamlines distorted.
$0.38<ak<0.44$	"Breaking" waves-vertical forward face of the wave; overturning and plunging of the waves.

+From VanDorn and Pazan (1975).

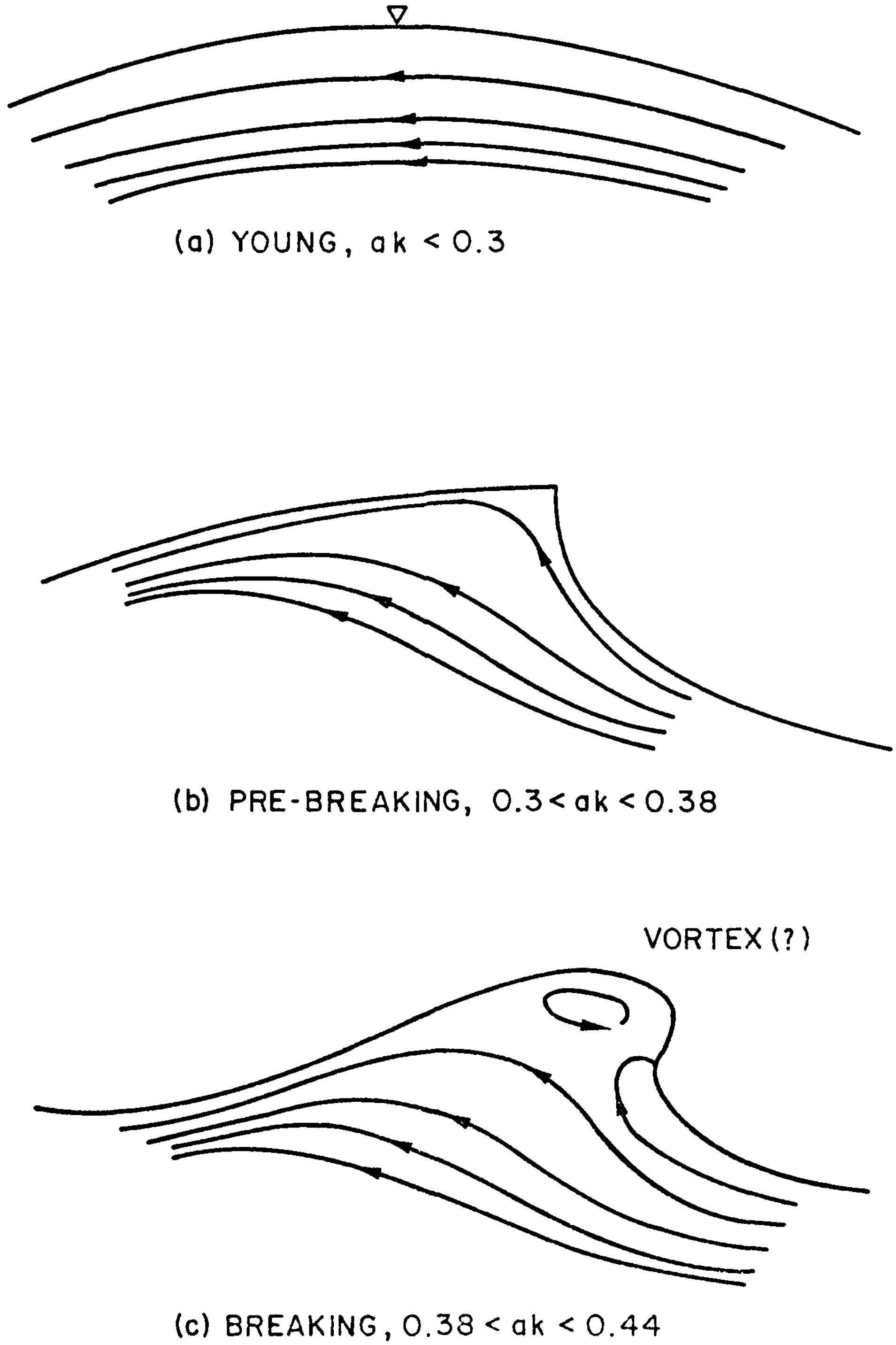


Figure 17 Regimes of deep water wave motion in a converging channel; from Van Dorn and Pazan (1975). The waves are shown in a coordinate system moving at the speed of uniform deep water waves.

The breaking intensity, defined by Van Dorn and Pazan in terms of the potential energy loss rate, was correlated with the potential energy increase before breaking. The energy dissipation due to breaking (normalized by the product of wave frequency and mean wave energy) was approximately a linear function of the growth rate of the waves. This led VanDorn and Pazan to suggest that history effects were likely to be important in any deterministic theory for wave breaking. In addition it was found that the energy losses after wave breaking were in equilibrium with the energy input due to the converging channel.

Donelan, Longuet-Higgins and Turner (1972) made brief field and laboratory studies of the breaking of deep water waves. It was observed in the open ocean that the appearance of white-capping breakers had a period of approximately twice the dominant wave period. This was confirmed in some small-scale wave channel experiments. The periodicity in the breaking waves was found to be determined by their velocity relative to the wave envelope or group. With the group velocity in deep water being one-half of the phase velocity c, the relative velocity was 0.5c and the time interval between whitecaps was then twice the wave period. This condition was thought to be valid for waves in a wind field which is relatively steady in strength and direction. A general discussion was given of the ramifications of this finding and its relevance to the airborne measurement of deep water surface wave phenomena.

Waves on Beaches. Peregrine (1983) has reviewed the fluid dynamics of breaking waves on beaches with the expressed view of understanding the basic processes that take place. Two primary areas were considered: the approach to wave breaking and the overturning process. In the approach to breaking the processes of wave steepening in shallow water, waves of limiting steepness, and wave instabilities were considered. Many aspects of

these topics already have been discussed to some extent in this report. Overturning of the wave surface also is an important part of the overall physical process of wave breaking. The recent numerical modeling of wave overturning has already been discussed here and the important flow regions in a wave approaching breaking are shown in Figure 11.

There is a large body of literature concerned with the properties of waves on and approaching beaches. Galvin (1968) has attempted to categorize the different regimes of wave breaking. Generally the sequence goes in the following order:

$$\begin{array}{c}\text{Spilling}\\ \downarrow \\ \text{Plunging}\\ \downarrow \\ \text{Collapsing}\\ \downarrow \\ \text{Surging.}\end{array}$$

From a series of experiments to study wave breaking on laboratory-scale beaches of slope m between m = 0.05 and 0.2, the different regimes were clearly delineated by the so-called "offshore parameter"

$$H_o/(\lambda_o m^2) \quad ,$$

as shown in Figure 18. Here H_o is the deep water wave height ($H_o = 2a$) and $\lambda_o = gT^2/2\pi$ is the deep water wave length, where T is the wave period. Similar wave characterization parameters have been proposed by others; see Hedges and Kirkgoz (1981). A similar ordering can be obtained in terms of the "inshore parameter"

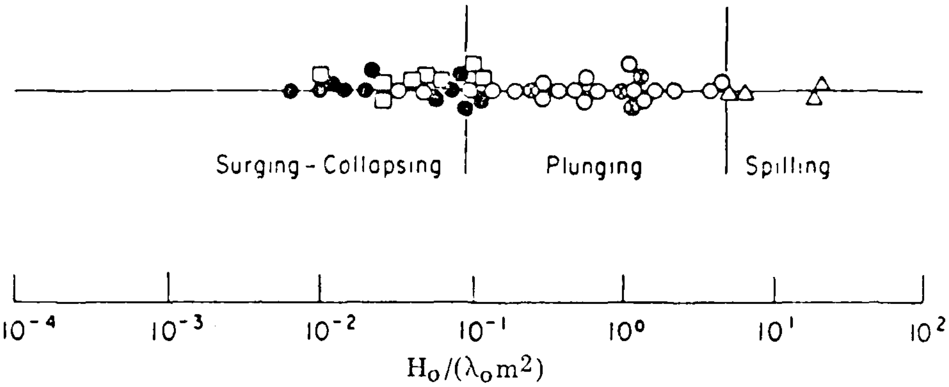


Figure 18 Breaker type characterized as a function of the "offshore parameter" $H_o/(\lambda_o m^2)$;; adapted from Galvin (1968). Δ, spilling; O, plunging; ⊗, plunging affected by reflection; ●, collapsing; □, surging.

$H_b/(mgT^2)$

where H_b is the actual breaker height and g is the gravitational acceleration. The transition values for the various breaker types are summarized in Table 4.

Table 4

Transition Values for Breakers on Beaches; from Galvin (1968)

Parameter	Spill-Plunge	Plunge-Surge
Offshore, $H_o/(\lambda_o m^2)$	4.8	0.09
Inshore, $H_b/(mgT^2)$	0.068	0.003

It should be noted that these parameters and the transitions between the various types of breakers were developed from a limited base of laboratory-scale data. However, the results do show that the different types of breakers can be recognized and ordered, at least for wave breaking on beaches.

Wave Breaking Over Obstacles. When waves are incident upon a submerged object with dimensions on the order of the wave length or larger, part of the wave energy is reflected from the object and part is transmitted past it. Steep waves produce distortions and additional wave interactions that further complicate the fluid/structure interaction between the waves and the obstacle. Ramberg and Bartholomew (1982) have studied the nonlinear effects of finite wave amplitude (steepness) on the wave flow over a submerged half-cylinder. An experimental program was conducted with an instrumented cylinder that spanned the entire width of a wave channel so that the flow was two-

dimensional. As a consequence of this study certain criteria were developed for the onset of wave breaking over the obstacle; these criteria are reviewed here. The work of Ramberg and Bartholomew was a follow-on to previous similar experiments with small-amplitude waves which have been reported by Miner et al (1983).

The experimental arrangement is described by Ramberg and Bartholomew (1982). Essentially the system consisted of an array of wave probes that was attached to a moving carriage. The carriage was traversed slowly along the wave channel under computer control to measure the spatial envelope of the wave amplitude. From this the reflection and transmission characteristics of the wave field could be determined. Various conditions of wave steepness and incipient wave breaking were obtained by varying the range of kd, where d is the water depth, and the relative depth d/a, where a is the radius of the half-cylinder. the experiments were conducted with kd = 0.6 to 2.5 and d/a = 1.25 to 2. These conditions provided shallow and intermediate water waves; the shallow water depth over the half-cylinder at d/a = 1.25 was particularly susceptible to the initiation of wave breaking.

The wave motion became nonlinear as the depth of water over the half-cylinder was decreased. Higher harmonics of the basic wave period began to appear, especially downstream from the cylinder. The second harmonic component (normalized by the fundamental) is plotted against the wave height in Figure 19 for two values of kd, 0.63 (shallow water) and 2.34 (intermediate-depth water). For the purposes of the experiment wave breaking was defined as the lowest incident wave height H at which all of the waves passing over the cylinder exhibited crest instabilities which led to spilling and plunging. One feature of the results is that the wave breaking does not depend upon wave steepness but on the local wave height over the cylinder.

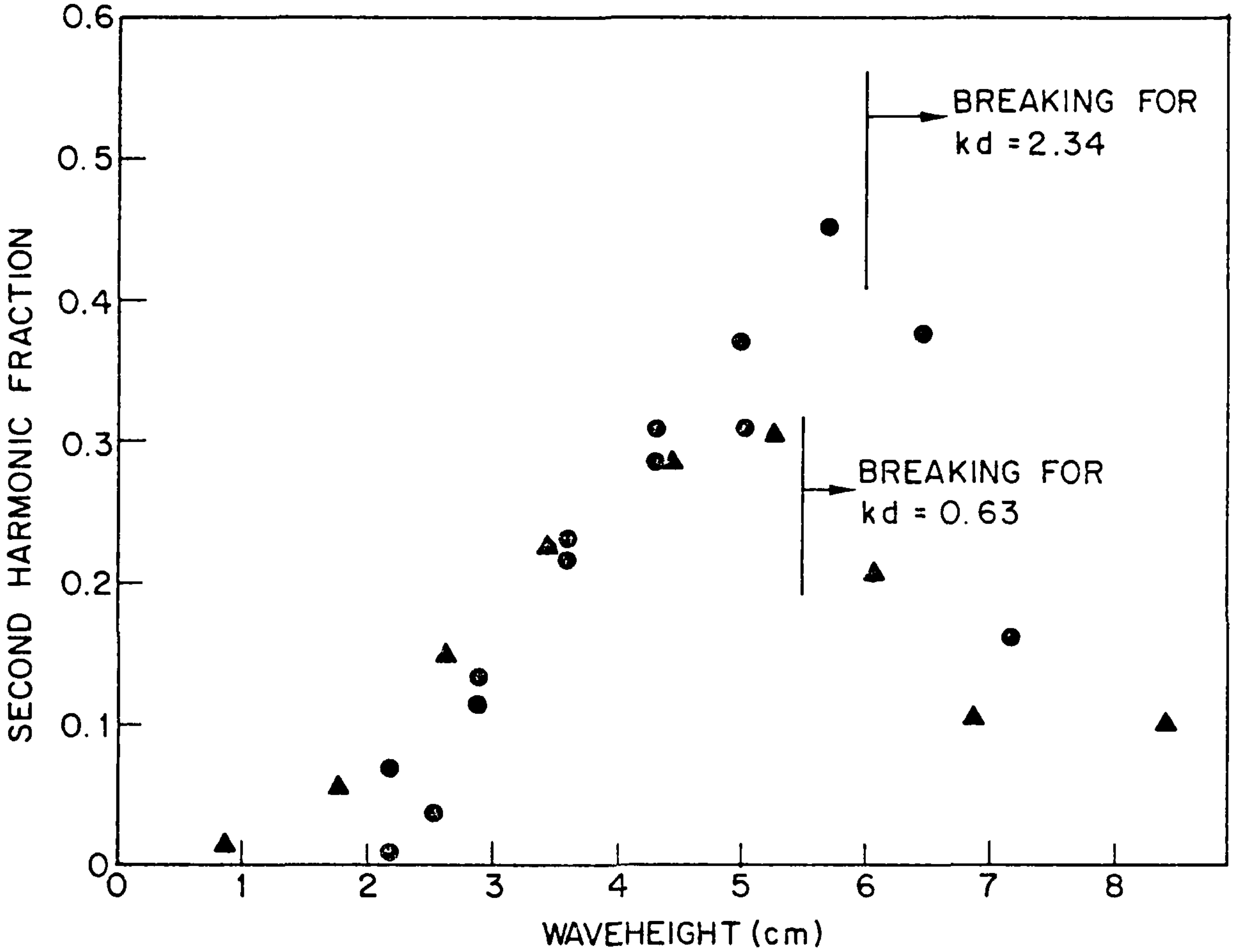


Figure 19 Growth of the second harmonic component of a wave incident upon a submerged half-cylinder, plotted as a function of the wave height H = 2a; from Ramberg and Bartholomew (1982). ●, kd = 0.63; ▲, kd = 2.34.

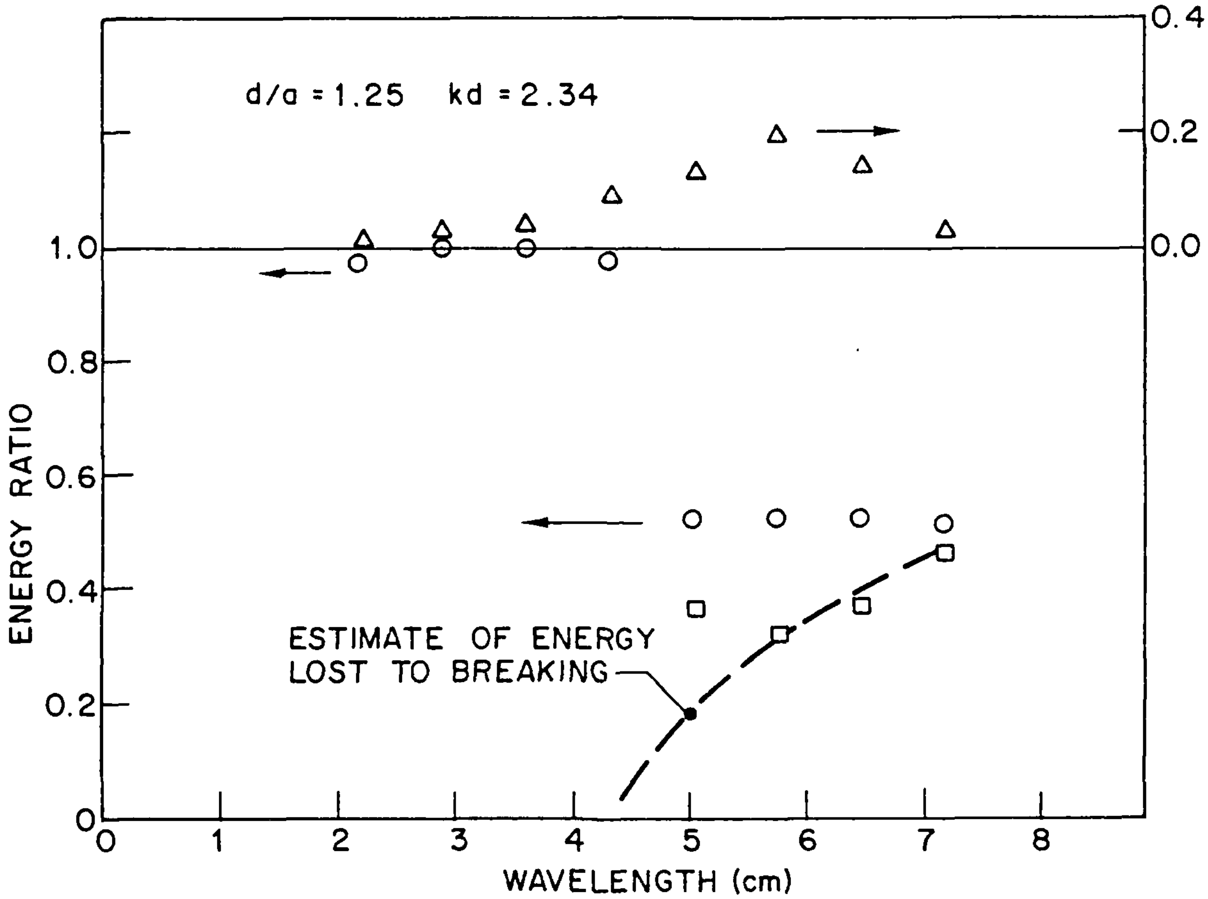


Figure 20 Estimates of the transmitted energy propagating downstream in the fundamental wave and its second harmonic, and of the energy lost to wave breaking, for a wave incident upon a submerged half-cylinder; from Ramberg and Bartholomew (1982). O, fundamental wave; Δ, second harmonic; □, energy lost to breaking.

The ratio of the wave height to the still water depth d' over the cylinder was 2a/d' = 0.375. Also the height of the second harmonic increased linearly until the breaking point, which was observed visually as noted on the figure, after which the higher harmonic components in the wave began to decrease rapidly.

Ramberg and Bartholomew (1982) estimated the energy lost to breaking by comparing the total energy actually found in the wave components downstream from the breaking point to the energy expected in the downstream fundamental wave component had the wave not broken. The energy content of various wave components, normalized by the transmitted energy of a non-breaking wave, is plotted in Figure 20 for the downstream fundamental and its second harmonic component. Note the large drop in the energy contained in the fundamental wave at the wave height $H \approx 5$ cm at which breaking took place. The energy lost to breaking was as much as 50 percent of the energy contained in an equivalent non-breaking wave under some conditions. These experiments were somewhat limited in scope but the results clearly show that careful experiments can elucidate many characteristics of breaking waves.

Kjeldsen (1979) studied the impact of deep water spilling breakers on submerged flat plates. The breaking waves were generated in a laboratory wave channel with converging side walls that caused the waves to steepen and break. The normalized shock pressure on the plate was found to be a function of the steepness ratio ε/S = 3.5 and higher. Maximum shock peaks on the obstacle were found at the crest height. This corresponded to the position of the maximum particle velocities in the breaking waves.

A steady oblique wave was generated by Hornung and Killen (1976) in a laboratory channel by placing a specially-designed obstacle in a steady flowing stream. The contour shape and

orientation of the obstacle were chosen appropriately to match the upstream free-stream water speed v_b, the phase speed c of the wave, and the angle γ between the wave front and the beach (or obstacle) contours. The oblique wave then is steady in a coordinate system fixed relative to that part of the wave that is just breaking. When the wave is moving obliquely toward a beach the breaking speed is equal in magnitude to v_b and then is related to c and γ by

$$v_b = c/\sin\gamma .$$

In the moving wave situation the flow is steady in a coordinate system moving with the velocity just before breaking. If these parameters are properly adjusted then the steady, oblique wave in a channel is analogous to the approach toward breaking of a steep unsteady wave on a sloping beach. The steep, but non-breaking, wave at normal incidence is farther offshore from the breaking region at any given time. This steep wave is similar in shape to the profile of the stationary oblique wave at a location along the wave crest ahead of the breaking region.

It was possible to properly contour the shape of the submerged obstacle, the flow rate, and the water depth by trial and error and to generate a steady breaking wave at a stationary location in the channel. This set-up was used to study the hydrodynamics of model surfboards which then remained in a fixed location relative to the breaking region of the wave.

Wave Breaking in Wind and Currents. Banner and Phillips (1974) have shown that the surface wind drift in the ocean reduces the maximum wave amplitude a_{MAX} and wave orbital velocity that can be achieved before breaking. If q is the magnitude of the surface drift at the point where the wave profile intersects the still water level and c is the wave speed, then

$$a_{MAX} = \frac{c^2}{2g}\left(1 - \frac{q}{c}\right)^2 \quad . \qquad (5.6)$$

The model was derived in a coordinate system moving with the wave, and the motion was assumed to be steady. Thus the applicability of the model is somewhat limited. This wave breaking criterion essentially is a modification of Stokes' classical breaking criterion for the zero surface current case. Banner and Phillips obtained some limited observations of a steady, standing wave that broke as wind was blown over the surface. However, they did not obtain any direct corroboration of the above equation. Phillips (1977) gives a related discussion of the breaking of waves in the presence of wind.

The influence of wind on wave breaking was studied experimentally by Banner and Melville (1976) in a laboratory channel. Steady non-breaking waves were generated by placing a cylindrical obstacle at an appropriate depth below the free surface of the flowing water. A statistically steady breaking wave was generated by placing a second submerged cylinder downstream of the first. In addition, wind was blown over the water surface in order to observe its influence on the waves. The onset of wave breaking was accompanied by the occurrence of a stagnation point at the air-water interface near the crest of the wave. The interfacial shear stress for the breaking wave was greatly enhanced by an order of magnitude from the shear stress occurring for an unbroken wave of the same wavelength. Melville (1977) drew attention to the importance of wave breaking to the transfer of mean momentum across the air-sea interface. A comparison of experimental results obtained in the field by a number of workers showed the importance of turbulence generation in the atmospheric boundary layer to the breaking waves on the surface of the water.

Nath and Ramsey (1974) and Kjeldsen and Myrhaug (1978) have proposed formulations for the prediction of breaking waves in

deep water. Both are statistical formulations which depend upon the types of wave spectrum formulations that are chosen to relate the wave height and the corresponding wave period. The onset of wave breaking is given by the breaking criterion

$$H_b = \sigma \, T_b^2$$

which is discussed earlier in this chapter. Both formulations are limited thus far to a unidirectional sea that is represented by an equilibrium spectrum, i.e. a fully-developed sea where the loss of wave energy to breaking is comparable to the energy supplied by the wind.

There are few additional studies of the combined actions of breaking waves and currents that are relevant to the problem of wave breaking in deep water. Most of the work that has been done to study wave-current interactions is theoretical in nature, and there is a dearth of experimental data against which existing theories can be tested. Peregrine (1976) has given a lengthy and detailed review of the interaction of water waves and currents. The simplifications that must be inherent in achieving a solution to the problem are detailed for various circumstances of approximation; e.g. the theory of water waves on large-scale currents, the corresponding problem of small-scale currents, and the interaction between waves and turbulence. An interesting discussion is given of the wave system generated by the motion of a surface ship in the seaway and of the importance of wave breaking in the overall energy balance of the ship wave system and wake. Thomas (1979) since has again reviewed the state of knowledge in the field of wave-current interactions. Wave breaking was not considered explicitly in the references that he cited.

The Breaking of Steady Waves. Duncan (1983) has developed onset criteria for the breaking of steady surface waves. These

criteria were obtained from observations of the waves produced by the steady motion of a submerged hydrofoil at a slight angle of attack. The surface wave pattern was generated downstream of the hydrofoil over a wide range of submergence depths. However, above a critical depth of the hydrofoil the wave breaking occurred spontaneously. Below that depth the waves were always regular except for a small range of depths near the critical value where the waves could be made to break by introducing artificial disturbances. Duncan introduced the disturbance in the form of a surface current which was equal to the foil speed.

The experiments were conducted at three foil towing speeds (60, 80 and 100 cm/sec) and two angles of attack (5 and 10^0). For these experiments at the critical submergence depth of the foil the average value (for ten tests) of the inclination angle from the horizontal of the wave's forward face was 17^0 and the wave steepness was ak = 0.314. These are less than the values that are usually calculated from classical higher-order wave theories (30^0 and ak = 0.443), as summarized by Longuet-Higgins (1980). In Duncan's experiments the breakers were spilling and the average wave steepness at breaking was comparable to the steepness values (ak ≈ 0.3 and slightly higher) at which Melville (1982) and Su et al (1982) observed the first appearance of spilling breakers. The waves observed by Melville and by Su et al were three-dimensional and crescent-shaped whereas Duncan's steady breaking waves were two-dimensional. The breakers were essentially deep water in character because the ratio of water depth to wavelength was always greater than $d/\lambda = 0.7$.

It was proposed by Duncan that the spontaneous wave breaking was caused by unstable subharmonic disturbances. This proposition seems plausible since the transient disturbances with a group velocity c_g equal to the foil towing speed had a wavelength of four times the length of the steady wave. At the

critical wave steepness of ak = 0.314 the theory of Longuet-Higgins (1978b) predicts that the fastest growing subharmonic instability is one which is four times the steady wavelength.

6. A FORECAST MODEL FOR WAVE BREAKING IN DEEP WATER

The results that have been discussed here thus far can form the basis of a forecast model for wave breaking in deep water. The basic approach here will be that taken first by Nath and Ramsey (1974, 1976) and more recently by Kjeldsen and Myrhaug (1978). Where possible the modelling approach will be modified to take account of any pertinent new results which have been obtained since the 1974 through 1978 time period when these studies were done. The criterion proposed thus far to predict the occurrence of wave breaking in deep water takes the form

$$H \geq H_b = \sigma T_b^2 \tag{6.1}$$

which was discussed in the previous section. Some estimates have been made of the breaking coefficient σ and they are summarized in Table 5.

Table 5

Breaking Coefficients for Ocean Surface Waves in Deep Water

Breaking Coefficient, σ (ft/sec^2)	Source; Method of Determination
0.87	Nath and Ramsey (1974, 1976); stream function theory.
0.49 (Linear-wave approximation)	This report; experiments of Melville (1982), Su et al (1982).
0.53 (Stokes' second-order correction)	

Following the approach of Kjeldsen and Myrhaug the joint probability density of the wave height h and the wave period t is given by p(h,t). The probability that a wave is breaking (the percentage of breaking waves in a given wave record) is given by

$$P_1 = P\left(H \geq h_b = \sigma t_b^2 \ \Omega \ 0 < T < \infty \right)$$

$$= \int_0^\infty \int_{h_b}^\infty p(h,t) \, dh \, dt. \qquad (6.2)$$

The probability that the wave height $H \geq h$ for the breaking waves in a given wave record is

$$P_2 = P\left(H \geq h \ \Omega \ H \geq h_b \right)$$

$$= P\left(\sigma \ T^2 > h \ \Omega \ H > h_b \right)$$

$$= P\left(T \geq t(h) = \left(\frac{h}{\sigma}\right)^{1/2} \Omega \ H \geq \sigma \ t_b^2 \right)$$

$$= \int_{\left(\frac{h}{\sigma}\right)^{1/2}}^\infty \int_{\sigma t^2}^\infty p(h,t) \, dh \, dt \ . \qquad (6.3)$$

Equation (6.3) represents the percentage of the entire sample of waves that are breaking and that are higher than the value h. The conditional probability that $H \geq h$, given that the wave breaks, is

$$P_3 = P\left(H \geq h \mid H \geq h_b \right) = P_2/P_1 \ . \qquad (6.4)$$

This represents the height distribution of the breaking waves.

If it is assumed that the sea surface can be represented by a stationary Gaussian random process with zero mean value and that the spectrum is narrow, then the commonly used wave energy

spectra (Pierson-Moskowitz, JONSWAP, etc.) can be employed. Examples of this approach are given by Kjeldsen and Myrhaug (1978). The latter looked at two different cases:

Case 1, where H and T are assumed to be statistically independent;

Case 2, where H and T are assumed to be statistically dependent.

Here we will give an example of Case 1 which was pursued in some detail by Kjeldsen and Myrhaug, and before them by Nath and Ramsey. When h and t are statistically independent,

$$p(h,t) = p(h)\, p(t). \tag{6.5}$$

Nath and Ramsey assumed that both h and t^2 were Rayleigh-distributed, which is somewhat arbitrary but the approach was thought to be reasonable from a practical standpoint. This particular approach employs the original expressions for h and t^2 given by Longuet-Higgins (1952) and Bretschneider (1959), respectively, so that

$$p(h) = \frac{2h}{\zeta^2}\, e^{-\left(\frac{h}{\zeta}\right)^2} \tag{6.6}$$

and

$$p(t) = \frac{4t^3}{\zeta^4}\, e^{-\left(\frac{t}{\zeta}\right)^4} . \tag{6.7}$$

The latter of the two is derived from the original formulation of $p(t^2)$ by Bretschneider. In these equations

$$\xi = \sqrt{\overline{H^2}} \tag{6.8}$$

is the rms (root mean square) value of the wave height and

$$\zeta^2 = \sqrt{\overline{T^4}} \tag{6.9}$$

is the rms value of $\overline{T^2}$, h is a specific zero-crossing wave height, and t is a specific zero-crossing wave period.

Based upon the work of Nath and Ramsey (1974, 1976) and Kjeldsen and Myrhaug (1978), and keeping in mind the constraints posed by the assumptions made thus far, the probabilities P_1, P_2, and P_3 are given by

$$P_1 = P(\text{"waves breaking"}) = \frac{k^2}{k^2+1}$$

$$P_2 = P(H \geqslant h \text{ and "waves breaking"}) \qquad (6.10)$$

$$= \frac{k^2}{k^2+1}\, e^{-\left(\frac{h}{\zeta}\right)^2 (1+k^2)} \qquad (6.11)$$

$$P_3 = P\left(H \geqslant h \text{ and } H \geqslant \sigma\, T^2 \right)$$

$$= e^{-\left(\frac{h}{\zeta}\right)^2 (1+k^2)} \quad . \qquad (6.12)$$

In these equations κ is a dimensionless empirical parameter related to the wave steepness, and it is defined by

$$k = \frac{\xi}{\sigma \zeta^2} \; . \qquad (6.13)$$

It is clear that the probabilities of wave breaking for a given wave record characterized by ξ and ζ^2 are dependent upon the choice of the breaking coefficient σ. Any predictions which are based upon the independence of h and t will be conservative relative to the analogous prediction when h and t are statistically dependent (Nath and Ramsey, 1974, 1976).

An example prediction of wave breaking at sea based upon actual in situ data was given by Kjeldsen and Myrhaug. The forecast was based upon data taken during a storm which occurred from 18-20 December 1977 at Tromsoflaket, off the coast of Norway. It was assumed that h = 16.4 ft (5m) and σ = 0.875 ft/

sec^2 (0.267 m/sec^2). The results are summarized in Figure 21. Note that the scale for P_3 is reduced by a factor of ten in the figure. During some portions of the recording period half of the waves present and greater than H = 16.4 ft (5m) were breaking. Some additional details of this example are given by Kjeldsen and Myrhaug who also derive equations for predicting the expected values of the maximum breaking wave height and the maximum overall wave height for a given wave record. A related discussion of this particular approach also is given by Nath and Ramsey (1974, 1976).

An example of Case 2 where the wave height h and the wave period t are statistically dependent is discussed briefly by Kjeldsen and Myrhaug in their report. The joint probability density of h and t is based upon the theoretical derivation given by Longuet-Higgins (1975). This joint probability density since has been improved by introducing an alternate formulation which more closely models real sea waves (Longuet-Higgins, 1983). The three wave breaking probabilities P_1, P_2 and P_3 are derived in principle from the prior work of Longuet-Higgins. However, the mathematics are much more complex than in the previous example. The two integrals that represent P_1 and P_2 must be numerically integrated to determine these functions. Then P_3 simply is given by P_2/P_1.

One suggested path toward deriving a general model for the forecast of breaking waves is given in Figure 22. It is based upon the overall approach taken thus far by Kjeldsen and Myrhaug and by Nath and Ramsey. Several critical steps are involved which require considerable further development and study. One is the specification of breaking criteria such as those given in Table 5. Other criteria which are more appropriate may be required, but the two developed thus far provide a start. Most of the wave spectra developed for engineering purposes which are in common use are limited to unidirectional, fully-developed

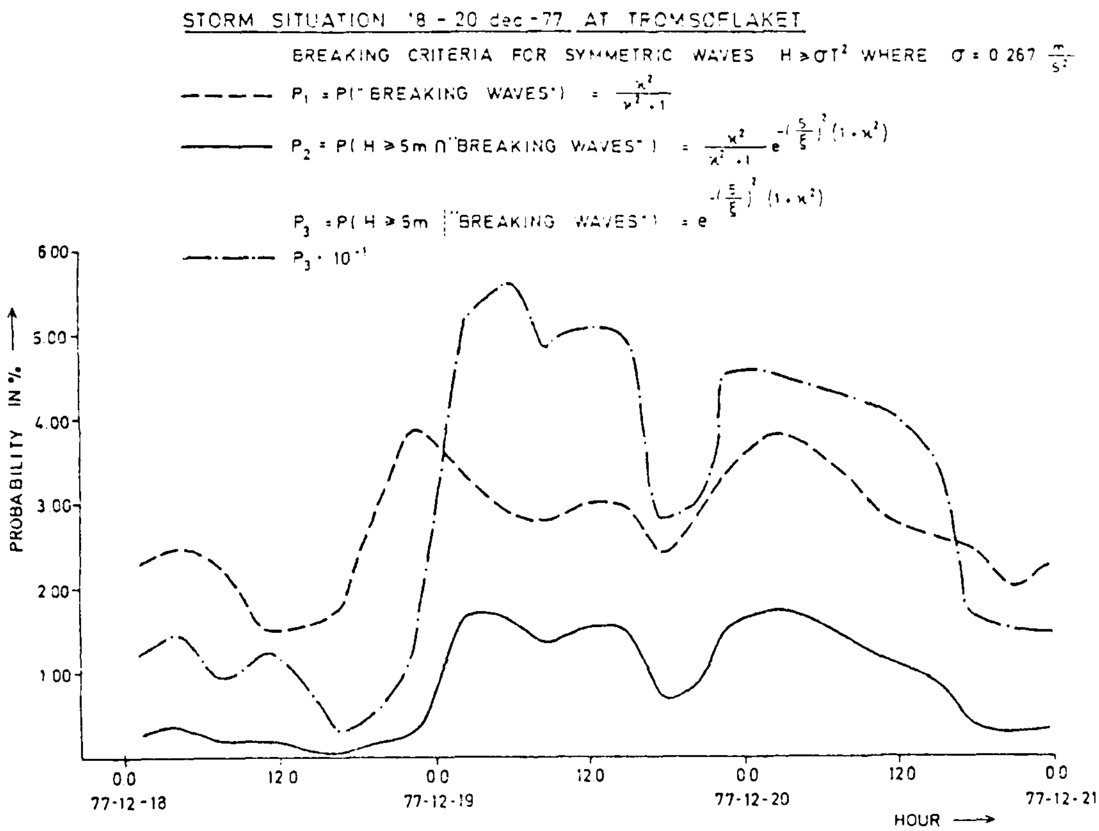


Figure 21 Probabilities for breaking waves in the storm period 18-20 December 1977, at Tromsøflaket off the Norwegian Coast; from Kjeldsen and Myrhaug (1978).

seas. Predictions of wave breaking are at this point limited by these constraints. It will be desirable and eventually necessary to have an approach which takes into account the directional properties of the sea surface. Then a wind wave field moving with one main direction can be super-imposed upon swell or a steady wave field (Kelvin ship waves, for example) moving in another direction. The steps given by the flow chart in Figure 22 provide a conceptual framework for the forecast of breaking waves. And the examples discussed in this chapter provide a simplified but reasonable start toward developing the capability to forecast the occurrence of breaking waves in deep water.

7. SUMMARY AND CONCLUDING REMARKS

There are essentially four types of breaking waves, as described by Galvin (1968) and many others. The first two types are the plunging breaker, in which the wave crest curls forward and plunges into the slope of the wave at some distance away from the crest; and the spilling breaker, in which the broken region tends to develop more gently from an instability at the crest and often forms a quasi-steady whitecap on the forward face of the wave. The spilling breaker is most common in deep water.

The third type, surging, sometimes develops as waves are incident upon a sloping beach. In this case, if the slope is very steep or the wave steepness is very small, the waves do not actually break but surge up and down to form a standing wave system with little or no air entrainment. A fourth type of breaking, collapsing, is considered to be a special limiting case of the plunging breaker. Collapsing occurs when the crest remains unbroken, but the lower part of the front face of the wave steepens, falls and then forms an irregular region of turbulent water.

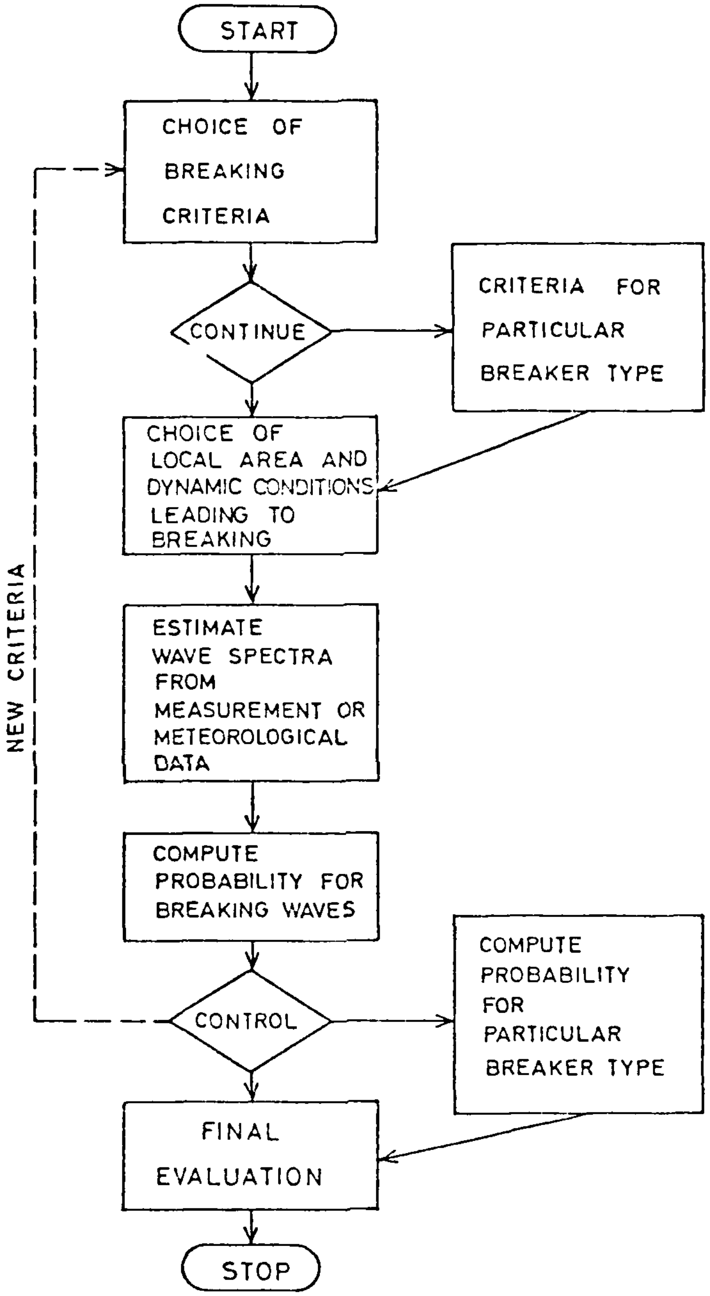


Figure 22 A conceptual model for the forecasting of breaking waves; from Kjeldsen and Myrhaug (1978).

Several advances toward an understanding of wave breaking have been made in recent years. These include the experimental characterization of the instability mechanisms which lead to wave breaking in deep water, mathematical models for the instability mechanisms, and numerical simulations of wave overturning and incipient breaking. Empirical and semi-empirical models have been proposed in a preliminary way to describe the breaking of steady and 'quasi-steady' waves.

The general features of breaking waves in deep and shallow water are known from many years of observation. However, the physical processes that contribute to the actual breaking are not well understood for the most part, although some progress has been made in recent years. General discussions of the physical processes involved in wave breaking are given by Galvin (1968) and by Cokelet (1977). Melville (1982) has described those factors which are most relevant to understanding the breaking of wave in deep water. Most recently Peregrine (1983) has reviewed what is known (and not known) about the overall dynamics of wave breaking and, particularly, about the breaking processes in shallow water and on beaches.

Little is known quantitatively about the processes of air entrainment in breaking waves. Various arguments have been made to apply the results obtained from studying other physically similar flows to this problem, but a reasonable approach to a well-ordered model is not yet clear. A more complete knowledge of the air entrainment processes will play an important role in the further development of plausible models for microwave radar scattering from breaking waves on the ocean surface.

It is possible on the basis of recent studies to suggest certain criteria for wave breaking under limited conditions. Most of the available evidence is qualitative in nature. There are few quantitative data but those which are available have

been used to develop a breaking criterion for deep water waves. The available results are summarized here primarily for deep water waves, but also a brief summary is given for intermediate and shallow water waves, or waves on beaches. Several special cases also are considered briefly. These include wave breaking over submerged obstacles, waves in wind and current fields, and steady breaking waves.

A forecast model for the breaking of deep water waves has been proposed (Nath and Ramsey, 1974, 1976; Kjeldsen and Myrhaug, 1978). In addition a breaking criterion has been formulated. Recent laboratory experiments to study the onset of wave breaking in deep water provide one means for quantifying this in terms of a breaking coefficient. An alternate means for quantifying this coefficient had been proposed on the basis of stream function wave theory. A conceptual approach to further development of the breaking forecast model has been proposed, and the critical steps which must be taken to achieve this development have been identified.

8. ACKNOWLEDGMENTS

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